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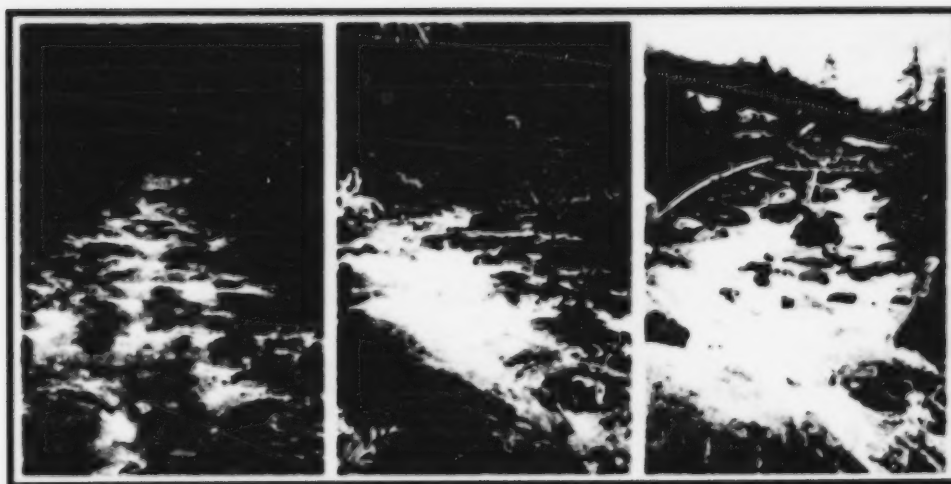
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Effects of Forest Harvesting and Regeneration on Peak Streamflow in a Coastal Watershed

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Cover photo: Salt dilution gauging reaches at Russell Creek, Russell Creek above Stephanie confluence, and Upper Stephanie Creek. Russell Creek is a sub-basin of the Tsitika River watershed on northeastern Vancouver Island, British Columbia.

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ABSTRACT

The issue of whether or not forest harvesting affects peak streamflows in Coastal British Columbia watersheds has been the subject of recent debate in the literature. In British Columbia, we use equivalent clearcut area (ECA) as an estimate of the potential for existing forest harvesting and regeneration to affect peak streamflow, but the link between ECA and peak streamflow has not yet been developed. This report works towards establishing that link, and also suggests the geomorphic significance of the changes in peak flow.

At Russell Creek, a fourth-order tributary sub-basin of the Tsitika River on northeastern Vancouver Island, a model of peak flow based on rainfall intensity was developed and used to demonstrate a decline in peak flows concurrent with a decline in ECA. The model divides up the 10-year data record into three distinct time periods with significantly different peak flow responses, such that the changes in peak flow can be assessed as a logarithmic function of a relative change in ECA. The mean response to a change in ECA of 10% was a change in peak flow of about 50%.

A specific gauge analysis reveals a major shift in gauge height consistent with channel scour that occurred at the time of two large peak flow events of 43 and 42.4 m³/s. The model predicts that at an ECA of 17.5%, these flows were increased by 70% compared to the unharvested state. The estimated effect of ECA conditions on flow frequencies suggests that channel forming events of 1–2-year return interval have been increased in both frequency and magnitude by about 70%. This effect has been substantiated by other studies at Russell Creek where significant changes in sediment transport have been attributed to declining ECA.

KEYWORDS

forestry, forest harvesting, regeneration, forest management, hydrology, streams, peak flow, sediment, sediment budget, sediment production, sediment yield, Vancouver Forest Region, British Columbia

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1. INTRODUCTION

The effects of forest harvesting on peak streamflow in forested watersheds have been the focus of much research in recent times. Peak flows have important implications in bridge and culvert design, and in channel forming processes. In Interior British Columbia watersheds, where peak flows are primarily generated by snowmelt, studies have shown quite clearly the linkage between forest harvesting and snow accumulation and melt, and their combined effect on peak flows. However, peak flow production from Coastal British Columbia watersheds is governed by a complex interplay between rain, rain-on-snow (ROS), and snowmelt processes. The effects of forest harvesting on these processes have proven far more difficult to sort out, with the result that different studies have produced conflicting results. Consequently, there has been continued debate in the literature over the effects of forest harvesting on peak flows in Coastal British Columbia watersheds (Harr 1986; Jones and Grant 1996; Thomas and Megahan 1998). These authors all base their conclusions on results of paired watershed experiments.

Much of the operational forest hydrology that is applied to coastal watersheds in British Columbia is based on research from the Pacific Northwest of the USA (e.g., Rothacher 1970; Ziemer 1981; Jones and Grant 1996 2001; Thomas and Megahan 1998, 2001). Research results from as early as the 1950s showed an increase in peak streamflow following forest harvesting (Maruyama and Inose 1952; Anderson and Hobbs 1959). However, several watershed studies since conducted in the Pacific Northwest have produced conflicting results. The scientific literature has reported increases, no change, and decreases in peak stream discharge following harvest and road building. The effects of clearcutting were evaluated in the Alsea River drainage on the Oregon coast. Krygier and Harr (1972) reported a significant increase in peak flows from Needle Branch and from two sub-basins of Deer Creek, which were at least 70% clearcut. The peak flows increased in size between 28 and 128%. At the Coyote Creek watershed in southwestern Oregon, the effects of different timber-harvesting practices on peak flows were evaluated. Harr et al. (1979) found that peak flow magnitude increased significantly in two small watersheds by 48 and 35% following shelterwood cutting and clearcutting, and 11% following small patch-cut harvesting in a third watershed. At Jamieson Creek in the Greater Vancouver Watershed, 19.2% of the drainage area was harvested over a period of six years. After harvest, winter storm peaks were increased by a maximum of 13.5%, while summer storm peaks were unaffected (Golding 1987).

The H.J. Andrews Experimental Forest was established in western Oregon in the early 1960s to study, among other things, the effects of harvest on streamflow. Jones and Grant (1996) re-analyzed 34 years of streamflow record and found detectable differences in the hydrograph shape associated with clearcutting and road construction. They reported that forest harvesting and associated road construction appeared to increase peak discharges by as much as 50% in small basins and 100% in large

basins. This study was pivotal in the debate regarding the effects of forestry on peak flows, because the authors claimed that the failure of earlier studies to detect the changes was due to inappropriate analytical techniques. They used the difference between the logarithms of matched peak flow pairs as a basis for the analysis¹. Thomas and Megahan (1998) stated that, contrary to the claims of Jones and Grant, analysis of covariance (ANCOVA) or a regression model is appropriate to analyze station pair data. Re-analyzing the same data set used by Jones and Grant (1996), they reached slightly different conclusions. The regression approach detected peak flow increases up to 90% for the smallest peak events in a small clearcut watershed, and up to 40% in a patch-cut and roaded watershed. They reported that treatment effects decreased as flow event size increased, and were not detectable for flows with a two-year return interval or greater. However, both studies were in agreement in that the effect diminished as event size increased.

Although a substantial number of studies have detected increases in magnitude of peak flows, researchers have reported that timber-harvesting activities had no effect on peak flows in other paired basin experiments. Rothacher (1965) found little or no increase in peak flows due to timber cutting in the Look-out Creek drainage in the western Oregon Cascades. From the examination of regression analysis by Duncan (1986, in Jones and Grant 1996), no change in peak flow magnitude could be detected following harvesting in the Deschutes watershed, located in the Cascade Mountains in southwestern Washington State. At the University of British Columbia's Malcom Knapp Research Forest, 60 km east of Vancouver, the paired watershed approach was used, and a decrease in peak flows was reported following harvesting of a small watershed (Cheng et al. 1975). The peak flow reduction was attributed to changes in the subsurface soil characteristics following harvesting, which forced water through deeper, slower routes. Similar results were obtained in a headwater basin in the H.J. Andrews Experimental Forest in Oregon, where Harr and McCorrison (1979) reported a reduction in peak flows of 32% following clearcut harvesting.

In snow-dominated Interior British Columbia watersheds, the standard paired watershed experiment has been highly successful at demonstrating increases in peak flow after harvesting (e.g., Cheng 1989; Troendle and King 1985). However, the complexity and variability of the processes that govern coastal peak flows suggest that the standard paired watershed approach may be inadequate to detect peak flow changes due to forestry. This is in part due to the high spatial variability of the factors that govern those processes. For example, the turbulent heat exchanges that dominate rain-on-snow melt are affected primarily by wind speed at the snow surface, which is altered by forest harvesting (Berris and Harr 1987). However, wind speed is

¹ I have found that using the log transformation tends to exaggerate the difference between control and treatment peak flows in a paired watershed analysis. The log transformation is not appropriate if the data are already normally distributed.

the most site-specific meteorological parameter that is routinely measured. In addition, freezing levels tend to vary widely within storms and from storm to storm, and rainfall distribution patterns are affected by freezing levels and by local topography. As a result, precipitation distribution patterns may not be comparable even between adjacent watersheds. Long-standing paired watershed studies generally rely on the long data records to compare pre- and post-harvesting hydrological conditions, but may not contain the details necessary to sort out these processes. The question of how to handle the data then becomes the subject of the debate. In view of the controversial nature of the peak flow debate, an alternative to the paired watershed approach seems to be warranted.

Harr (1986) recognized the need to separate events of different types in order to successfully determine the effects of forest harvesting on peak streamflow. Recognizing the fact that in any given Coastal watershed, peak flows may be either increased or decreased by forest harvesting, he describes the kind of scenario that may lead to either result. Forest harvesting may lead to a reduction in peak flows when there is rain turning to snow or vice-versa. If precipitation begins as snow, the snow caught in the canopy at a forested site will be washed off by the rain that follows, thereby augmenting rainfall. In an opening, the snow that accumulates on the ground will initially absorb the rain to affect a delay in runoff from the clearcut. However, Harr points out that these events tend to be small and therefore not particularly significant. The largest peak flows are generated by warm rain on ripe snowpacks, and these events are also the ones most likely to be augmented by harvesting because of the increased wind speed at the snow surface in a clearcut relative to that under a canopy.

One way of dealing with this effect is to sort the events according to size and to examine only the largest events. One possible sorting criterion is return interval. In examining peak streamflow following the application of two partial harvesting systems in small catchments at Flume Creek in the Roberts Creek Study forest on the Sunshine Coast, B.C., Hudson (2001a) noted a similar phenomenon to that described by Harr (1986, described above). Many of the flows were unaffected by harvesting, and two cases were observed in which the post harvesting flows were decreased relative to the unharvested control. However, among the larger events (>0.5 -year return interval) an average of 52% were significantly increased by harvesting, and among those affected, the mean increase in peak flow was as much as 200% at 38% canopy removal.

The issue of the potential effects of forestry on peak flows is of much concern to forestry, fisheries, and water managers in British Columbia. Although it is generally assumed that the large events (i.e., 25-to-100-year floods) have a far greater effect on stream channels than the effects of forest harvesting, the rate of channel recovery between those events can be significantly affected by peak flows that are enhanced by forestry. Because of the ambiguity in the literature on the subject of peak flows and harvesting, many forest managers and hydrologists have tended to discount the role of forest harvesting in its effect on

peak flows. However, a body of evidence is now growing to support the idea that significant and substantial changes in peak flows can indeed occur as a result of forestry activities in rain-dominated Coastal streams (Hudson 2001a; Chapman et al., in review; Hetherington 1987).

Potential effects on peak flows are related not only to forest harvesting, but also to subsequent regeneration. Assuming that harvesting alters peak flows, then it is important to define the way in which forest regeneration restores peak flows to pre-harvest levels. The concept of equivalent clearcut area (ECA)² encompasses both forest harvesting and regeneration. Methods of estimating hydrologic recovery (and hence, ECA) have been the focus of much attention in British Columbia (Hudson 2000a and 2000b; Spittlehouse 1998). These results describe relationships between regenerating stand structure, snow accumulation, and melt and rainfall interception, but have not established a link between ECA and peak flows.

This paper reports on an analysis of the peak flow response of a Coastal British Columbia watershed with ongoing harvesting to rainfall characteristics in an effort to establish a link between changes in the ECA of the watershed and the subsequent peak flow response.

2. STUDY AREA

Russell Creek is a fourth-order tributary sub-basin of the Tsitika River on northeastern Vancouver Island (Figure 1). It drains an area of 30.8 km² and ranges in elevation from 275 to 1715 m. The lower watershed is relatively gently sloped, and the main channel has a gradient of 4%. The basin is bowl shaped and has two bowl-shaped third-order tributaries, with steep head-water slopes. Forty-eight per cent of the watershed lies within the rain-on-snow zone (300–800-m elevation band) and the remainder is in the snowpack zone (above 800 m). Russell Creek has a history of harvesting development dating back to the early eighties. About 642.3 ha have been harvested within the rain-on-snow zone, and 244 ha within the snowpack zone; this equates to 29% of the total area harvested, and 43.4% of the area of the ROS zone.

The stream gauging site was installed in November 1991, and operated by Water Survey of Canada (WSC). Stage was measured and recorded using a nitrogen bubbling system connected to a mercury manometer and Stevens A-35 chart recorder. In the fall of 1997, a bubbling transducer connected to a data log-

² Equivalent clearcut area (ECA) is the area that has been harvested, cleared, or burned with consideration given to the silvicultural system, regeneration growth, and location within the watershed (BCMOF and BCMOE 1999). I.e., ECA is the area that is clearcut, but with a reduction factor to account for the hydrologic recovery due to forest regeneration. In many cases, ECA may be a factor in limiting forest harvesting in watersheds that are sensitive to potential changes in peak streamflow (e.g., community watersheds or important fish streams) or in watersheds with a long history of harvesting. However, the current method of determining hydrologic recovery for Coastal sites, as described in the watershed assessment procedure (WAP) guidebooks (BCMOF and BCMOE 1999), is outdated. The method described in Hudson 2000 is now routinely used by most proponents.

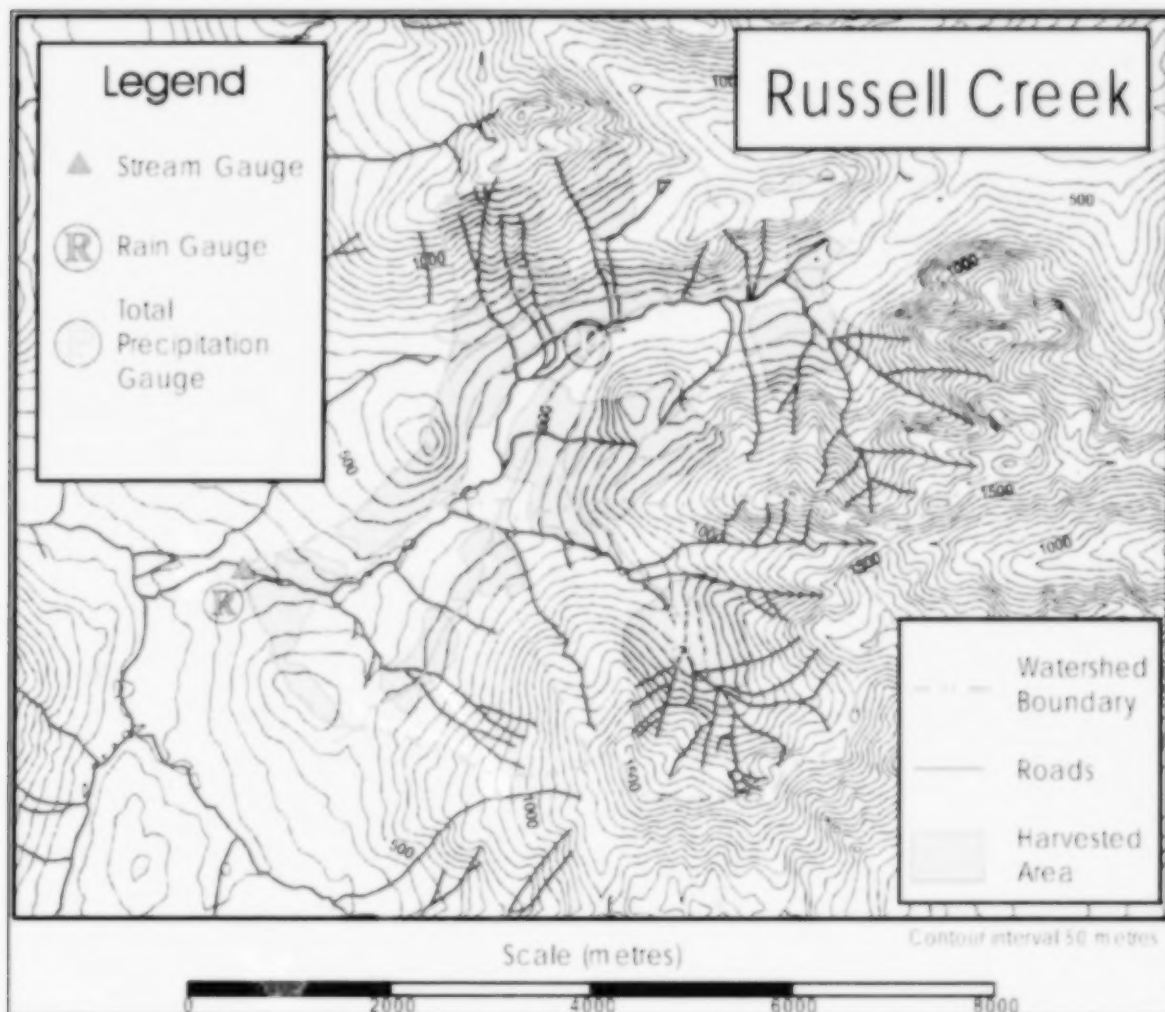


Figure 1. Map of Russell Creek showing the locations of the main stream gauge (Russell Creek near the mouth) and the rain and total precipitation gauges used to determine the basin average precipitation.

ger was installed and operated in conjunction with the manometer, and thereafter monitoring was carried out jointly by the British Columbia Ministry of Forests and Water Survey of Canada. From 1991 to 1999, flow rating was done by WSC using standard current metering techniques. Starting in the summer of 2000, salt dilution gauging was tested and developed for use at Russell Creek, and the success of the method has led to adopting it as the standard method of gauging streamflow in that watershed (Hudson and Fraser 2002).

Rainfall measurement also commenced in November 1991 at a site near the stream gauge, using a tipping bucket rain gauge

with a 1-mm resolution connected to a data logger. Total rainfall and mean air temperature were recorded every 5 min. Additional precipitation gauging sites were established at upper Stephanie Creek (Elevation of 830 m a.s.l.) in 1994 and at Russell Creek at TSI20 (aka Upper Russell, elevation 490 m a.s.l.) in 1997 (Figure 1 and Figure 2). At these sites, total precipitation was measured using a PVC standpipe gauge, as well as rainfall (by tipping bucket gauge), air temperature, global solar radiation, humidity, and wind speed and direction, recorded every 15 min with a high-resolution data logger. This network has provided the data by which precipitation distribution analysis can be performed to calculate basin average rainfall.

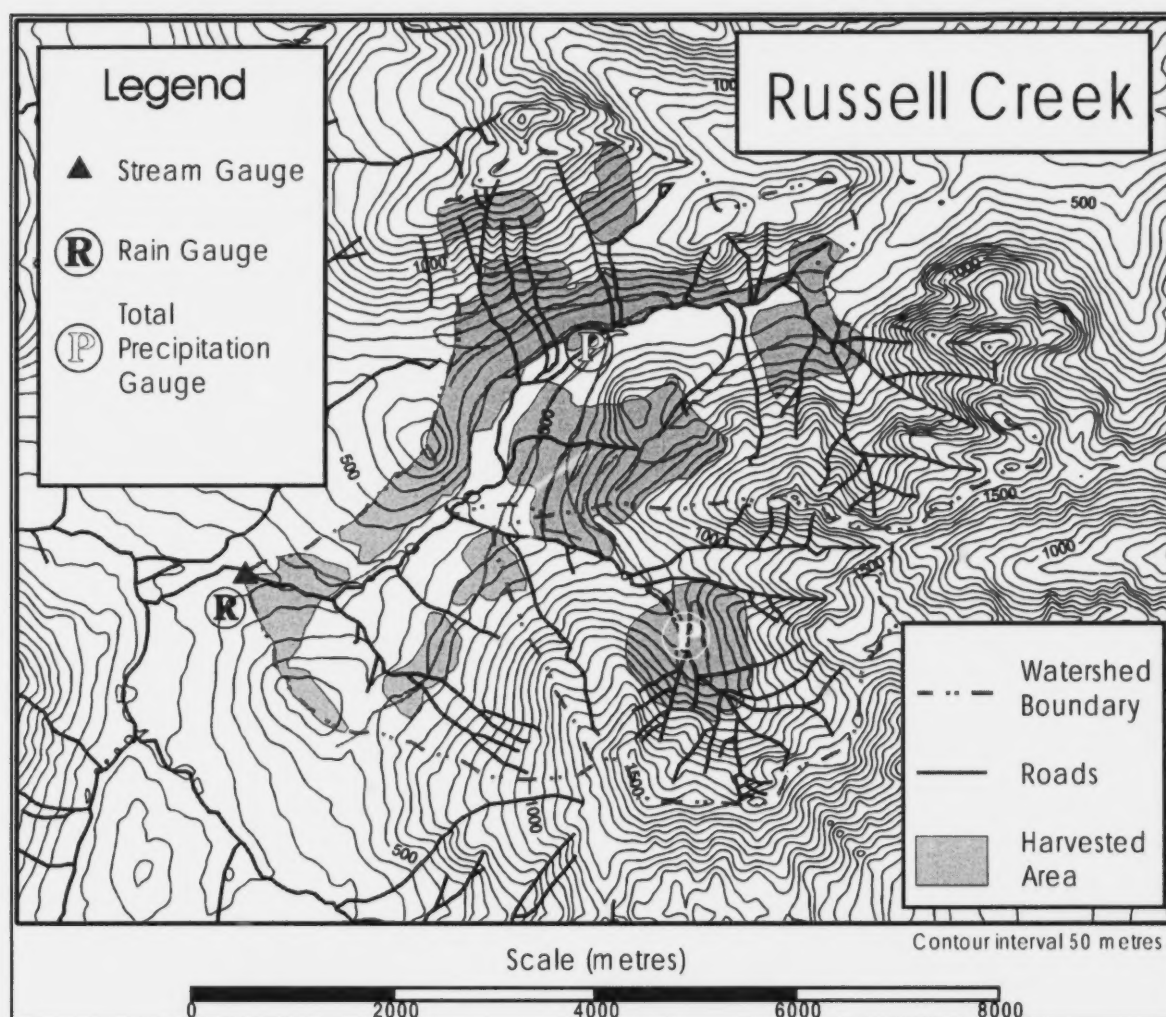


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3. METHODS

3.1. Event and Parameter Selection

Using mean hourly flow data, all hydrological events in the record were selected that had a peak flow of 1 m³/s or greater. A total of 350 events were identified. The events were sorted according to their peak flow, and the return interval was calculated. All events with a peak flow of less than 5 m³/s were discarded: the aim of this screening criterion was to discard the lower half of the peak flows, and although somewhat arbitrary, the 5 m³/s flow corresponds to a return interval of about 0.6 years.³ Any remaining events for which there were no precipitation data were also discarded at this point. For each event, several parameters were selected that were considered as possible variables in a rainfall-based peak-flow model. These parameters include flow parameters and meteorological parameters.

3.1.1. Flow parameters

Flow parameters include:

- The peak flow; i.e., the maximum hourly streamflow recorded for the event (Q_p , m³/s).
- The base flow, defined as the antecedent streamflow immediately prior to the onset of rainfall that caused the event (Q_{BF} , m³/s). Initially, the minimum flow that occurred prior to the event was also considered as another potential base flow quantity, but was rejected because the base flow as defined above resulted in a higher R^2 when correlated with rainfall parameters.
- Lag time or time-to-peak (T_p), defined as the time in hours between the occurrence of the base flow and the peak flow.

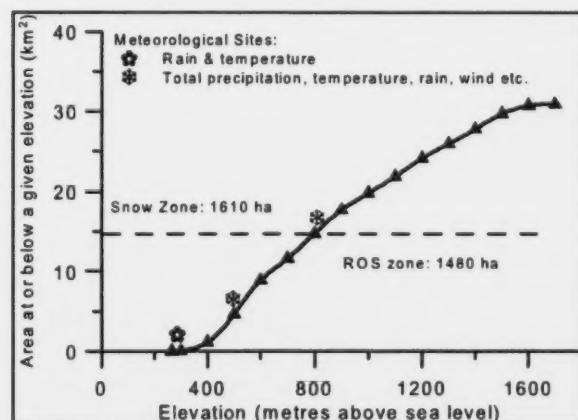


Figure 2. Area elevation curve for Russell Creek.

³ An annual maximum flow series was constructed using Weibull's return interval for rain-on-snow events; however, there is uncertainty regarding the return interval of a given flow because of the effect of ECA on peak flows. This is discussed in more detail in section 5.1.

3.1.2. Meteorological parameters

Several parameters related to the precipitation intensity-duration characteristics of the storm were quantified. At Russell Main, only rainfall was used because snow was not directly measured at that site. At Upper Russell and at Upper Stephanie, two sets of precipitation parameters were quantified: one based on rainfall and a second set based on total precipitation. These included:

- Maximum precipitation intensities of 1-, 3-, 6-, 12-, and 24-h duration that occurred during the storm (R_1 , R_3 , etc. for rainfall; P_1 , P_3 , etc. for total precipitation). These maxima were selected from running totals of rainfall derived from the 5-min rainfall record at the main rain gauge site near the stream gauge.
- The total storm precipitation and storm rainfall that occurred during each storm (P_s , R_s), and the duration in hours of that rainfall. The duration was classified and further reduced using the classification system presented in Table 1, where the parameter D was used as an index of event duration in developing the peak flow model.

The meteorological parameters described above were used in the precipitation distribution analysis to determine basin average rainfall. The basin average parameters were then used in the peak flow modeling procedure.

3.2. Precipitation Distribution

Precipitation distribution analysis consisted of the following elements:

- Separation of rainfall and snow using gauge data from Upper Stephanie and Upper Russell Creek.
- Establishing precipitation gradients.
- Analysis of temperature lapse rates in order to define freezing levels. This is the main influence on rainfall distribution, and is more important than the precipitation gradients.
- Development of predictive relationships to use during periods when there was only one rain gauge in operation.

Table 1. Storm classification.

Event duration (h)	Effective duration (h)	Classification (D) *
3-9	6	1
9-15	12	2
15-21	18	3
21-27	24	4
27-33	30	5
>33	36	6

* Note that the quantity D is actually an ordinal variable, meaning that although it is used to classify the storms, it has an internal scale that might be proportional to its effect on peak flow.

3.2.1. Separation of gauge data

PVC standpipe gauges are in fairly wide use by various agencies around British Columbia, including the BC Ministry of Forests (BCMOF); the BC Ministry of Water, Air and Land Protection (BCWALP, formerly BC Ministry of the Environment); BC Hydro; BC Ministry of Transportation and Highways (BMOTH); and others. These gauges are easy and relatively inexpensive to build and operate. However, one of the characteristics of the gauge is that the PVC expands and contracts with temperature, resulting in a diurnal fluctuation of fluid levels in the absence of precipitation or evaporation. The thermal expansion depends not only on air temperature, but also on solar radiation incident on the gauge. For a given temperature, the thermal expansion coefficient is higher in direct sunlight on a clear day than a cloudy day. A program was developed to correct for these temperature/radiation-based gauge errors.

When the expansion/contraction errors are removed, there are still minor random errors that are related to the transducer and data logger resolution, as well as to incomplete expansion correction. These gauge errors are dealt with by accumulating negative errors until there are enough positive values to cancel the negative values. These corrections are sufficient to produce an hourly data file that is reasonably accurate to within 2-3 hs. A critical temperature is used to separate the total precipitation into rain and snow. Quick et al. (1995) recommend a critical temperature of 2°C for mean daily data, in which case the critical temperature is the mean daily temperature below which the rain blends into snow at 0°C. By experimentation and by observation, a critical temperature of 0.8°C has been found to work well for hourly data. In this case, the critical temperature is treated as an "on/off" switch: above 0.8° it is raining, and below that temperature it is snowing. A correction for gauge undercatch is then applied to the snow component using mean hourly wind speed, based on Goodison's (1978) gauge catch deficiency relationships. The undercatch relationship for a Universal gauge is considered applicable to a 16-inch PVC standpipe gauge.⁴ Finally, tipping bucket gauge error due to the melting of snow caught in the gauge funnel is removed. This error can be seen clearly using 6-h data. With the processing described above, generally the 6-h rainfall from the tipping bucket gauge and the rainfall calculated from the standpipe gauge should be in close agreement (the gauge resolution has been found to be 1-2 mm). Following a period of cold weather with snow, this type of error will appear as an apparent rainfall with no change registered on the standpipe gauge, that occurs in the 6-h period after a rise in temperature.

3.2.2. Calculation of basin average precipitation

The method used to calculate basin average precipitation involved matching of precipitation gradients to the area-elevation curve (Figure 2). The watershed was divided into 100 metre elevation bands and the area of each band was measured. There-

fore by establishing temperature and precipitation gradients between the meteorological sites, those gradients were used together with the area-elevation data to calculate the precipitation within each band, and the temperature gradients were used to calculate where the critical temperature and the freezing levels occurred. This was then used to calculate the relative proportion of rain and snow in each elevation band. The methods used in the University of British Columbia (UBC) watershed model were adapted for this purpose (Quick et al. 1995).

Essentially, the UBC model is run on a daily time step and precipitation gradients and lapse rates are calculated from daily temperature and precipitation data. During the period from October 1997 to present there were three sites on which to base the precipitation distribution (Russell Main, Upper Russell and Upper Stephanie, Figure 1). In October 1995, the Upper Stephanie gauge was activated. These periods were used to investigate patterns of temperature and precipitation gradients that could be applied to the period prior to the fall of 1995, during which only rain and temperature were measured at Russell Main.

3.2.2.1. Precipitation gradients

The precipitation gradient between Russell Main and Upper Stephanie sites varied with no apparent pattern. Sometimes the gradient was positive, and sometimes negative. Quick et al. (1995) make use of temperature at a base site and the temperature lapse rate to help define the precipitation gradient. The precipitation gradient is needed to interpolate between the sites and to extrapolate above Upper Stephanie. When temperatures are low, the saturated adiabatic lapse rate is close to the dry adiabatic lapse rate, and at high temperatures it is low. This results in snowfall being highly influenced by orography, while summer rainfall is relatively insensitive to elevation. At Russell Creek, there appeared to be a family of parallel lines in which the gradient was inversely proportional to storm size, but there was no discernible pattern that could be linked to any property of the rainfall or temperature data at Russell Main to indicate which line to use.

A more useful relationship turned out to be the total storm precipitation at Upper Russell and at Upper Stephanie (P_u), as a function of storm rainfall (R_s) measured at Russell Main (Figure 3). There were similar relationships for each of the maximum intensity parameters (R_{30} , R_{15} , etc.). Thus, if rainfall parameters are known or can be predicted for Upper Stephanie and Upper Russell, then precipitation gradients can be calculated from those values. There was a single linear relationship between total storm precipitation at Upper Russell and Russell Main. The coefficient of the relationship was 1.02, which is not significantly different from 1. At Stephanie Creek, the relationship to rainfall at Russell Main has a coefficient of 1.2 and an offset that was sometimes positive and sometimes negative, such that a dummy variable could be used to forecast the storm precipitation at Upper Stephanie with an R^2 of 97.5% (Figure 3, lower graph). However as with the gradient, it was not possible to discern a pattern based on temperature and rainfall data at Russell Main that could be used to determine which form of

⁴Barry Goodison, Environment Canada Atmospheric Environment Service, Toronto Ontario; personal communication, May 2001.

the equation to use. Eventually the dummy variable D_R was treated as a calibration parameter that defaults to zero, but can be set at ± 1 to maintain data continuity.

Precipitation-elevation gradients were calculated for each storm and used to determine the precipitation at the mid-point of each elevation band. As recommended by Quick et al. (1995), the precipitation gradient is set to zero above an elevation equal to about two-thirds of the barrier height, which at Russell Creek is about 1100 m. Measured data were used to calculate the gradients if available, otherwise they were calculated using the relationships as described above. There was a separate relationship for each of the maximum intensity parameters similar to the one for storm precipitation as described above. The basin average precipitation is then calculated as a weighted average, using the proportion of the watershed area in each band as the weighting factors.

3.2.2.2. Temperature lapse rates

Temperature gradients are of primary importance to the modeling of rainfall driven peak flows because they govern the distribution of rain and snow in the watershed. The critical temperature (T_{crit}) is used to determine the form of precipitation; between the T_{crit} and zero, the precipitation will blend from rain to snow. Therefore, the freezing level and the critical temperature level are needed to separate rain from snow.

As with the precipitation gradients, there was an apparent relationship that appeared to be a series of parallel lines describing

the temperature gradients, but no discernible way of predicting which line should be in effect. Instead, a simpler relationship existed between Russell Main and Upper Stephanie that was used to calculate lapse rates in the period when only Russell Main was in operation (Figure 4, lower graph). Again borrowing from Quick et al. (1995), low lapse rates tend to occur in warmer weather, and high lapse rates in cold weather. Inversion conditions are usually associated with clear-weather overnight cooling. Thus they do not occur often in this data set because it represents periods of storm activity.

The critical temperature of 2°C (as discussed above) for mean daily temperature data is an approximation. The division of precipitation into rain and snow was done while processing the data from the snow gauges, as discussed in section 3.2.1. Converting the hourly rain and snow data to daily totals, the proportion of daily precipitation that falls as snow forms an inverse linear relationship with mean daily temperature between 0 and 2°C (Figure 4, upper graph). This validates the accuracy of the 2°C critical temperature. The precision is not particularly high, but there is always a loss of precision when moving from hourly to daily data.

3.2.2.3. Calculation of basin average

An Excel spreadsheet template was designed for the purpose of doing the calculations. For each storm, a mean daily temperature lapse rate was calculated to find the critical tempera-

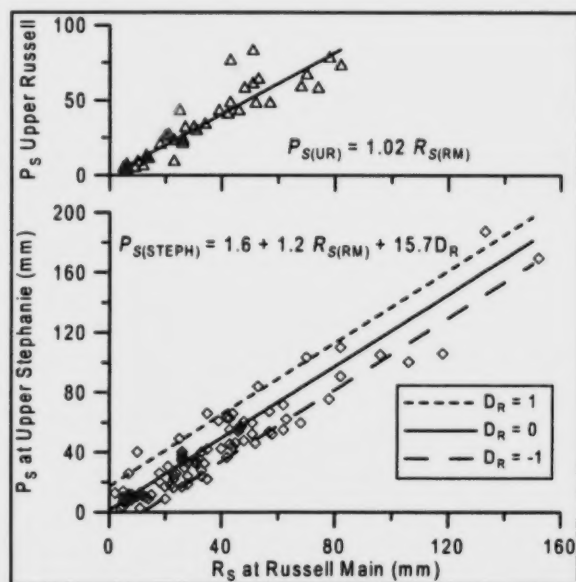


Figure 3. Precipitation at Upper Russell (top) and Upper Stephanie gauges relative to storm rainfall at Russell Main.

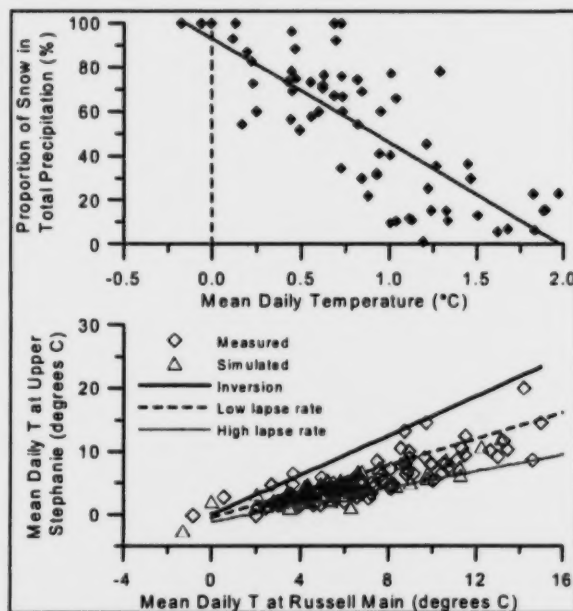


Figure 4. Lapse rates of mean daily temperature (lower graph) are calculated from daily temperature data from Russell Main and Upper Stephanie. The three lines on the graph represent different lapse conditions.

ture and freezing elevations. The lapse rate was calculated from observed temperature data, if available, for Stephanie Creek. Prior to 1995, a temperature was predicted for Upper Stephanie using an appropriate equation from Figure 4, and used with the Russell Main daily temperature to calculate a lapse rate. Therefore, for elevations where the mean daily temperature is between the critical temperature and 0°C, the weighted precipitation was scaled towards zero using linear interpolation, thereby removing the snow component. The result is basin-average rainfall. This procedure was repeated for each rainfall parameter.

For example, basin-average precipitation is calculated for two storms in the fall of 1998 (**Appendix A**). In these two examples the influence of the temperature gradients is clear; in the case of the example calculation shown, the 24-h maximum storm intensity for the 09 December event at Russell Main is almost 80% greater than for the 19 November event, but because of the cooler temperature and steeper lapse rate in the December 09 event the basin-average 24-h rainfall intensity is 40% less.

3.3. Storm Classification

Snow conditions in the watershed were not monitored directly. To determine snowpack conditions associated with each event, the UBC watershed model was calibrated to the watershed, using the daily flow, precipitation, and temperature records. The snowpack conditions were derived from the model output, including the aerial coverage of snow prior to the event, and the change in snow water equivalent that occurred during the event. This information allowed for an objective classification of events into three types, as follows:

1. Rain-only events: These events generally involved only small changes in snow water equivalent, of less than ± 4 cm of water equivalent. These events include summer and early fall rains when the watershed was free of snow, or events when there was a small amount of snow in the watershed, but not enough to contribute significantly to runoff. Some of these events involved a significant snowpack; but if the temperature is low (i.e., cold rain) the water yield from the snowpack is minimal, and effectively the event is no different from rain only.

2. Rain-on-snow events: These events were characterized by a loss of water from the snowpack of more than 4 cm. These events were also characterized by a significant component of direct runoff from snowmelt. The antecedent snow cover was usually at least 30%.

3. Snowmelt events: This class involved a rise in streamflow under snowpack conditions without appreciable rainfall.

Since the aim of this research is to derive a rainfall-based peak flow model, the third type of event was removed from the data set. The first two event types were classified using the variable T as follows:

$T=1$ for rain-on-snow, and $T=0$ for rain only.

3.4. Determination of ECA

To assess the ECA of Russell Creek and the changes in ECA that occurred from 1991 to 2001, the approach described by Hudson (2000b) was used. Because the method is based on a determination of stand height in regenerating clearcut openings, forest regeneration survey data were obtained from MacMillan Bloedel Limited (now Weyerhaeuser) in 1999 and updated by collecting stand height measurements in the summer of that year. Because the regeneration surveys were done in different years on stands of varying ages, these surveys, along with the ground truthing done in the summer of 1999, provided the data to develop stand height growth curves for the Russell Creek openings (**Table 2**). Although a standard growth and yield curve takes the form of a logistic function, it was found that the range of the stand heights in their current condition allowed a linear approximation to be used to forecast stand heights from 1991 to present (**Figure 5**). This model was tested against a standard growth and yield model and the results were almost identical.

Russell Creek is in Snow Accumulation Zone 2. The rain-on-snow zone below 800 m occupies 42.5% of the watershed area, and the remainder is in the snow accumulation zone. The equation describing hydrologic recovery (R , expressed as a proportion) is

$$R = (1 - e^{-0.22(Ht - T_R)})^{0.70} \quad (1)$$

The recovery threshold T_R (m) for the rain-on-snow zone can be calculated as

$$T_R = 0.00414(elev) - 0.717 + 0.5 \quad (2)$$

and for the snow accumulation zone as

$$T_R = 0.00353(elev) - 0.28 \quad (3)$$

where,

$elev$ is the elevation in metres a.s.l. of the regenerating opening for which the recovery is to be determined.

ECA is then calculated as:

$$ECA = A(1 - p \cdot R) \quad (4)$$

where,

A is the opening area, and

p is the proportion of the opening occupied by regeneration of stand height Ht .

Equations 1 to 4 are used to calculate the ECA of an opening. For a watershed, the ECAs of the individual openings are totaled and expressed as a percentage of the watershed area. Examples of ECA calculation for 1992 and 1999 at Russell Creek are given in **Table 2**.

3.5. Peak Flow Model Development

After sorting and filtering out the smaller storms and the snowmelt-dominated events as described above, there were 164 events

Table 2. Examples of calculating ECA for Russell Creek.

Opening number	Opening area (ha)	Year harvested	Year surveyed	Lead species	Canopy height (m)	Series	Elev. (m)	Threshold (m)	Stand height		Recovery		ECA	
									1992 (m)	1999 (m)	1992 (p)	1999 (p)	1992 (ha)	1999 (ha)
382201	28.4	1983	1997	Hw	5.8	1	350	1.2	3.0	7.7	0.448	0.823	15.7	5.0
382204	15.6	1988	1991	Hw	0.2	1	520	1.9	0.0	4.3	0.000	0.533	15.6	7.3
382401	19.0	1983	1996	Hw	5.6	1	330	1.1	3.0	7.7	0.460	0.826	10.3	3.3
391104	32.7	1992	1998	Hw	0.6	1	520	1.9	0.0	1.6	0.000	0.000	32.7	32.7
391201	76.8	1988				0	925	3.0	0.0	2.5	0.000	0.000	76.8	76.8
391201	25.6	1988	1996	Ba	2.6	2	925	3.0	0.3	6.1	0.000	0.613	25.6	9.9
391202	9.5	1993	1998	Yc	0.5	1	980	3.2		1.0		0.000	0.0	9.5
391301	38.0	1985	1995	Hw	4.6	1.5	585	2.2	2.2	7.5	0.000	0.768	38.0	8.8
391301	40.0	1985	1996	Hw	5.8	1.5	585	2.2	2.2	7.5	0.000	0.768	40.0	9.3
391302	85.6	1983	1993	Hw	3.8	1	575	2.2	3.0	7.7	0.280	0.781	61.6	18.8
391303	86.0	1986	1996	Hw	3.9	1.5	660	2.5	1.4	6.7	0.000	0.702	86.0	25.7
391304	91.4	1989	1992	Ba	0.3	1	880	2.8	0.0	3.6	0.000	0.282	91.4	65.6
391305	59.6	1985	1997	Hw	7.5	2	490	1.8	2.8	8.6	0.312	0.837	41.0	9.7
391306	43.0	1986	1996	Hw	4.7	2	580	2.2	1.9	7.8	0.000	0.785	43.0	9.2
391308	12.4	1987	1996	Hw	5.3	1	540	2.0	0.3	5.0	0.000	0.597	12.4	5.0
391308	12.4	1987				0	660	2.5	0.0	3.0	0.000	0.208	12.4	9.8
391311	34.0	1996	1997	Hw	0.4	2	505	1.9		0.0		0.000	0.0	34.0
391312	29.8	1995	1997	Hw	0.4	2	540	2.0		0.3		0.000	0.0	29.8
391402	38.6	1992	1997	Hw	0.8	2	670	2.6	0.0	2.8	0.000	0.115	38.6	34.2
393101	41.6	1996				2	1050	3.4		0.0	0.000	0.000	0.0	41.6
393204	39.6	1980		Hw		1	600	2.3	5.0	9.7	0.572	0.859	17.0	5.6
?	26.8	1997				2	730	2.8		0.0		0.000	0.0	26.8
Totals														
(ha)	886.4												658.0	478.4
(%)	28.7												21.3	15.5

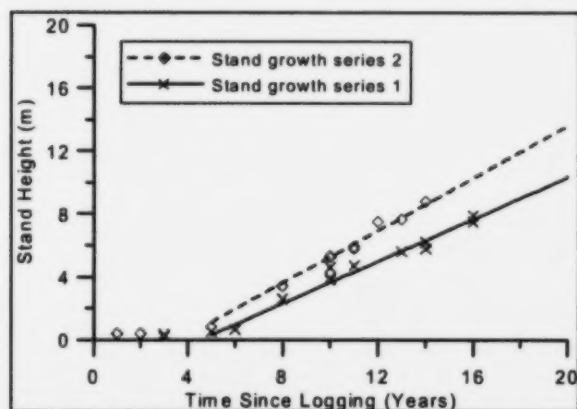


Figure 5. Relationships to calculate and forecast stand height of regenerating openings at Russell Creek.

remaining for analysis (**Appendix B**). To develop a peak flow model, all the parameters in that table were considered in the model, as well as interaction terms between the classification variables (T and D) and the precipitation parameters.

There are various possible approaches to develop a model to predict peak flows at Russell Creek using the various parameters and event classifications as described above. One approach is to lump all the data together; another approach is to break the data down according to event type or event duration in an effort to determine the effects of different processes on the occurrence of peak flows. All of these approaches were investigated using a combination of stepwise regression and regression comparison analysis. Eventually a systematic approach was developed, as follows:

1. A combination of correlation and stepwise regression analysis was used initially to identify a potential set of parameters for a model, so that a set of parameters could be

identified that could be used to test for differences among regression models for different time periods. At this stage in the model-selection process, the potential effects of changes in forest cover over time were not considered.

2. The data set was divided into time periods by water year, and regression comparison analysis was used to identify differences between groupings when the same model was applied to different groups.

3. The regression comparison analysis identified three preliminary groupings of data into three time periods, in which a common regression equation for each water year within each time period was identified, while the regression equations were significantly different between periods.

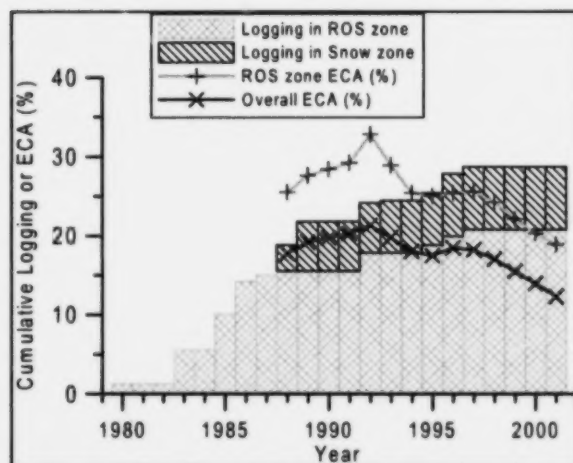


Figure 6. Harvesting history (bars) and ECA (symbols and line), Russell Creek.

4. Best subsets regression was then applied to each period in order to optimize the common model. The purpose of this analysis was to select the best model for each group from the available parameters that could be applied to all time periods. This included all parameters, and was not limited by the results of the stepwise regression.

5. Following the model selection process, the model was tested on individual water years in a regression comparison analysis to see if the groupings would come out differently on an optimized model. This resulted in Period 2 being split into two subgroups with the regression equations that were significantly different, albeit marginally so.

4. RESULTS

Harvesting in Russell Creek commenced in 1980 and reached almost 22% of the watershed within nine years. At that point harvesting slowed down, and regeneration growth began to achieve some hydrologic recovery. Recovery occurs most rapidly in the earliest stages of regeneration growth once the stand height has passed the recovery threshold (Hudson 2000b). As a result, ECA reached a peak in 1992 and has been declining since then (Figure 6). Because most of the harvesting was concentrated in the rain-on-snow zone (300–800-m elevation band, Figure 4.1), both the overall ECA and the ECA specific to the rain-on-snow zone were calculated. ECA within the rain-on-snow zone was substantially higher than the overall ECA. Overall ECA peaked in 1992 at 21.3%, but within the rain-on-snow zone, ECA in 1992 was at 32.8%.

Regression comparison revealed that the peak flow model for Periods 2a and 2b were significantly different from each other (Table 3), but in reality there is very little difference between the two equations. When a prediction limit is calculated for each of Period P2a and Period P2b, the overlap between the two periods in terms of their predictive ability is such that there is no practical value in maintaining the separation.

Table 3. Peak flow model is of the following form: $Q_P = b_1 Q_{BF} + b_2 R_{24} + b_3 R_S + b_4 T + b_5 T \cdot R_S + b_6 T \cdot R_6$.

Time Period		b_1	b_2	b_3	b_4	b_5	b_6	n/S.E.
P1: 11/1991 - 11/1992	Coefficient	1.2751	0.0087	0.3077	-0.0180	-0.3341	0.7489	23
	t-ratio	6.34	0.14	5.59	-0.01	-2.44	2.25	2.165
P2: 11/1992 - 05/1997	Coefficient	1.1273	0.0616	0.1268	4.3878	0.1263	-0.1275	68
	t-ratio	12.41	2.70	7.69	4.67	4.98	-2.04	2.399
P2a: 11/1992 - 05/1995	Coefficient	1.1361	0.0914	0.0988	3.0647	-0.0005	0.1136	33
	t-ratio	14.27	3.54	5.56	3.10	-0.01	1.20	1.355
P2b: 10/1995 - 05/1997	Coefficient	0.9659	0.0586	0.1368	6.1690	0.1473	-0.1651	35
	t-ratio	7.07	2.14	6.77	5.14	5.15	-2.30	2.460
P3: 06/1997 - 11/2001	Coefficient	1.0140	0.1415	0.0048	4.7548	0.0012	0.0243	68
	t-ratio	8.62	8.55	0.31	5.87	0.06	0.75	1.811

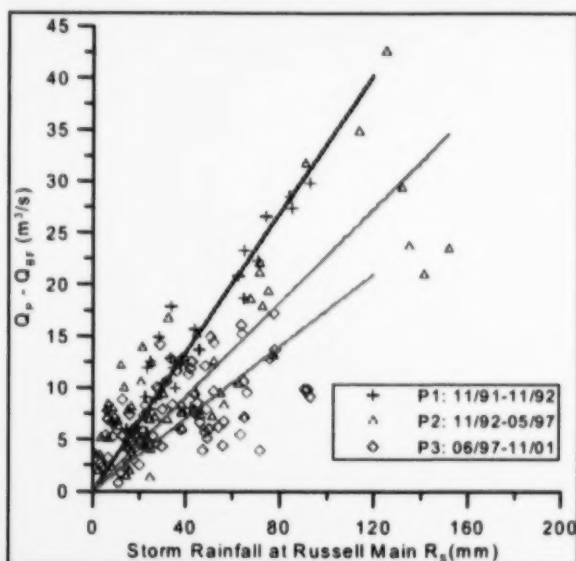


Figure 7. Peak flow over base flow as a function of storm rainfall, as measured at Russell Main, showing the three distinct time periods. At this point, the regression lines are all significantly different, but the relationships are not well defined.

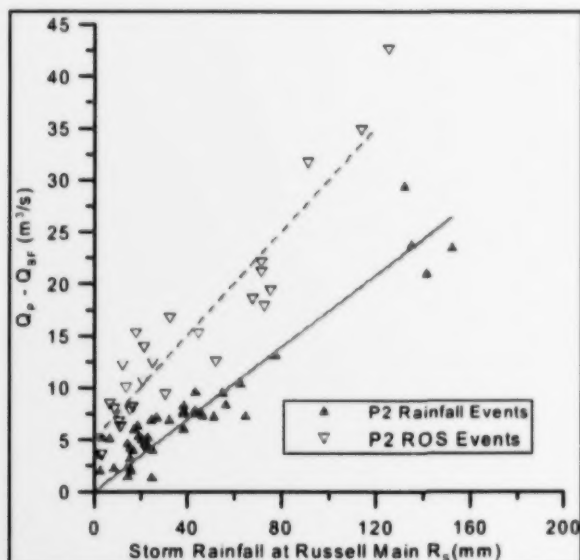


Figure 8. Looking at period P2 separately, the relationship is greatly improved by classifying events into two types: those caused by rainfall only and those that involved rain-on-snow conditions.

The early attempts to model the differences in peak flow response between periods representing different ECA conditions were based on rainfall at Russell Main (Figure 7). At this stage, the relationships between peak flow over base flow ($Q_p - Q_{bf}$) are significantly different from each other, but are not well defined. Looking at Period P2 separately, the relationship is greatly improved by classifying events into two types: those caused by rainfall only and those that involved rain-on-snow conditions (Figure 8). Note that the regression lines for rain events (solid line) and rain-on-snow events (dashed line) are different. This indicates that the peak flow model distinguished rain-on-snow conditions from rainfall conditions by an offset (i.e., the intercept of the dashed line) as well as an interaction with a rainfall parameter (i.e., the difference in slope between the dashed line and the solid line). Further improvements to the predictive ability of the model resulted from using basin average rainfall parameters instead of the parameters from a reference site. The identified model resulted in well defined relationships between peak flow over base flow and the effective rainfall R_e , defined by a linear combination of the basin average rainfall parameters identified by the model selection process (Figure 9).

The model selection process identified a model of the form:

$$Q_p = b_1 Q_{bf} + b_2 R_{24} + b_3 R_s + b_4 T + b_5 T \cdot R_s + b_6 T \cdot R_e \quad (5)$$

Regression comparison revealed that there were four time periods with significantly different regression equations of the above form (Table 3). The first term in the model is base flow, and the coefficients are close to 1, indicating that base flow is essen-

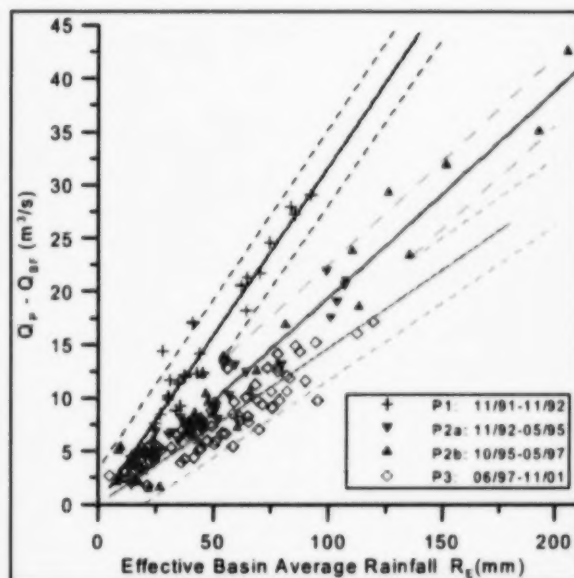


Figure 9. Peak flow model (Equation 9) applied to three time periods at Russell Creek.

tially an offset variable. The second and third terms are the basic rainfall terms, and they indicate that peak flows are essentially driven by long duration rainfall—the total storm rainfall and the maximum intensity of 24-h duration that occurred during the storm. This probably reflects the dominance of the large (18+ h duration) storms over the smaller ones, and the fact that the shorter duration storms are represented by the variable R_3 , because it encompasses the entire duration of the storm. It is also interesting that neither the storm duration nor the time to peak were significant to peak streamflow, although there was a relationship between the two parameters, albeit a poorly defined one. From this we must conclude that peak flows at Russell Creek are not sensitive to short-duration high-intensity rainfall. Also note that for each time period, not all the model coefficients are significant. For example in Period P1, the second term is not significant, indicating that the basic rainfall variable is the total storm rainfall and that the 24-h maximum intensity is not important, while for Period P3, the reverse is true.

The fourth, fifth, and sixth terms in the model represent an adjustment factor for warm rain on snow. The fourth term is an offset factor, while the fifth and sixth terms are factors that adjust the slope of the relationship for rain-on-snow conditions. Again, not all terms are significant in each time period. In Period P1, term 4 is insignificant, while in Period P3, terms 5 and 6 are insignificant. This indicates that rain-on-snow conditions are more significant during large storms at high ECA, while at lower ECA the rain-on-snow conditions act to boost peak flows but are independent of storm size. It also appears that when ECA is higher, rain-on-snow conditions are more likely to react to shorter duration intensities; in fact, the 3-h maximum intensity could have been substituted for the 6-h maximum without any significant reduction in R^2 .

Equation 5 can be rearranged into the following form:

$$Q_P - b_1 Q_{BF} = b_2 R_{24} + b_3 R_3 + b_4 T + b_5 T \cdot R_3 + b_6 T \cdot R_6 \quad (6)$$

The right side of the equation can be thought of as "effective storm rainfall". The first two terms are basic rainfall factors that account for the two major factors that influence peak flows in rain dominated environments: the total storm rainfall, and a factor to account for the rainfall intensity. If we define this as the basic storm rainfall (R_{SB}), then

$$R_{SB} = \frac{b_2 R_{24} + b_3 R_3}{b_2 + b_3} \quad (7)$$

where,

R_{SB} is in mm of rain.

Dividing by the sum of the coefficients adjusts the basic storm rainfall to the actual mean basin rainfall for the time period defined by the model. This quantity becomes the basis for the peak flow model and because it is a synthetic parameter, it is important to perform a "continuity check" to ensure that there is no bias in it. To do this continuity check, R_{SB} is compared to the measured storm rainfall R_3 at Russell Main (Figure 10). The graph reveals that there is no change in the relationship between periods, ensuring that the model has not been biased.

The last three terms in Equation 6 are a factor to adjust the rainfall to account for the additional water yielded by the snow-pack under rain-on-snow conditions. Adjusting to the mean basin-average rainfall as in Equation 7, this factor becomes:

$$ROS_{adj} = \frac{b_4 T + b_5 T \cdot R_3 + b_6 T \cdot R_6}{b_2 + b_3} \quad (8)$$

The right side of Equation 6 then becomes:

$$R_{E,i} = R_{SB,i} + ROS_{adj,i} \quad (9)$$

where,

$R_{E,i}$ denotes "effective basin average rainfall" for period i .

The rise in streamflow from base flow to peak flow ($Q_P - Q_{BF}$) then becomes a simple linear function of $R_{E,i}$ for each time period (Figure 9). This is a more useful form of the peak flow model than Equation 6 because it allows the three time periods to be compared directly (Figure 9).

For each time period and sub-period, regression comparison analysis indicated that the regression line for each period is significantly different from that of each other time period. The solid lines represent Equation 9 as it is applied to each period. The dashed lines represent a 90% prediction interval about each regression line. Periods 2a and 2b were combined because their prediction intervals overlap almost completely. That is, they are so close that there is no practical difference between them. A comparison between Periods P3 and P1 suggests that for a change in ECA of just over 5%, the flows in Period P1 are

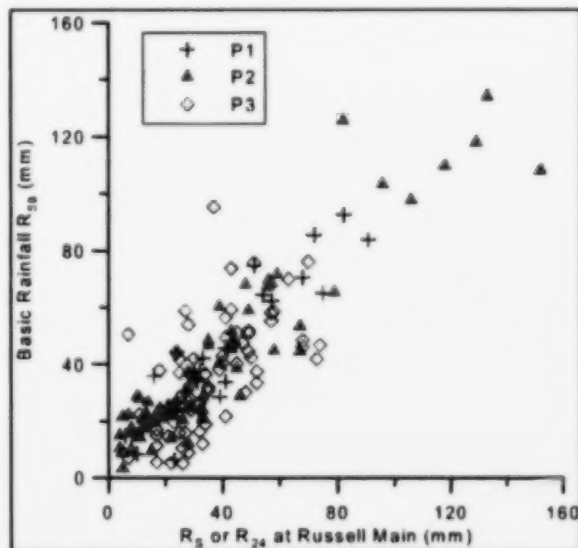


Figure 10. Graph to act as a continuity check to ensure that there is no bias in the model. R_{SB} is plotted against R_3 for Periods P1 and P2, and against R_{24} for Period P3 (see Table 4). The relationship between the derived and measured parameters remains unchanged.

more than doubled for comparable R_p compared to Period P3. However, the ranges of the effective rainfall are different with the result that this is probably misleading.

The final step in the process is to use Equation 9 to derive a model that can be used to test for changes in peak flow in relation to differences in ECA. This model is described below:

- R_{pb} and ROS_{adj} were calculated for each of Periods P1, P2, and P3.

- This derived data set was lumped together and a common peak flow model was derived using a classification variable to distinguish Periods P1, P2, and P3 (Table 4).

- Peak flow was then regressed against base flow, R_{pb} , ROS_{adj} , the classification variables and interaction terms, resulting in the following equation:

$$Q_p = 1.14 \cdot Q_{br} + 0.187 \cdot S1 \cdot R_{pb} + 0.139 \cdot S2 \cdot R_{pb} + 0.190 \cdot S1 \cdot ROS_{adj} + 0.146 \cdot S2 \cdot ROS_{adj} \quad (10)$$

where, $R^2 = 98\%$ and standard error = 2.06 m³/s.

- Equation 10 was then reduced to a set of 3 specific equations representing the mean ECA conditions of each time period, by solving for the classification variables (Table 4).

To apply this model, all three equations were used to calculate the expected peak flow in each time period under conditions represented by the mean ECA for each period. Those expected peak flows were then compared to the actual peak flow for each storm, and a percent difference between actual and expected flow was calculated (ΔQ_p). For example, peak flows observed during Period P1 were compared to peak flows calculated for period P2 using Equation 10.2 and for Period P3 using Equation 10.3 (see equations in Table 4). These percent differences in peak flow were then related to the difference between the actual ECA during the event and the mean ECA that corresponds to each of Period P2 and P3 (Table 4). Because there is a large amount of overlap between the three time periods at the low end of the range, not all peak flow changes are significant with respect to a given change in ECA (Figure 9). For each time period, if the observed peak flow fell within the prediction limit of the equation representing the period for which the contrast was being made, then the comparison was deemed not to have been affected by harvesting, and ΔQ_p was assigned a value of 0% (Figure 11). For example, to determine a difference in flow between an observed event in Period P1

and a flow that would have occurred if the ECA had been similar to that of Period P2, refer to the middle graph of Figure 11. If the observed flow in question is above the upper prediction limit of Period P2 (represented by the dashed line), then the value of ΔQ_p is the difference between the observed flow and the flow calculated by Equation 10.2, expressed as a percentage of the average of the two flows. Similarly, to determine the value of ΔQ_p for the same event compared to ECA conditions represented by Period P3, refer to the lower graph. In either case, if the observed P1 flow is below the upper prediction limit of either P2 or P3, the value of ΔQ_p is equal to zero (Appendix C). For a ΔQ_p between observed flows in Period 3 compared to Periods P1 or P2, the observed P3 flow must be below the lower prediction limit of Period P1 or P2 (Figure 11, upper and middle graphs, respectively) to be considered affected by current ECA, otherwise it is unaffected and assigned a value of zero.

Table 4. Final form of a model to test the effects of changing ECA on peak flows.

Period Classification	Equat. #	Mean ECA	Peak flow equation
S1,S2 = (1,1)	10.1	20.8%	$Q_{p1} = 1.14Q_{br1} + 0.326R_{pb1} + 0.336ROS_{adj1}$
S1,S2 = (1,0)	10.2	18.9%	$Q_{p2} = 1.14Q_{br2} + 0.187R_{pb2} + 0.190ROS_{adj2}$
S1,S2 = (0,1)	10.3	15.4%	$Q_{p3} = 1.14Q_{br3} + 0.139R_{pb3} + 0.146ROS_{adj3}$

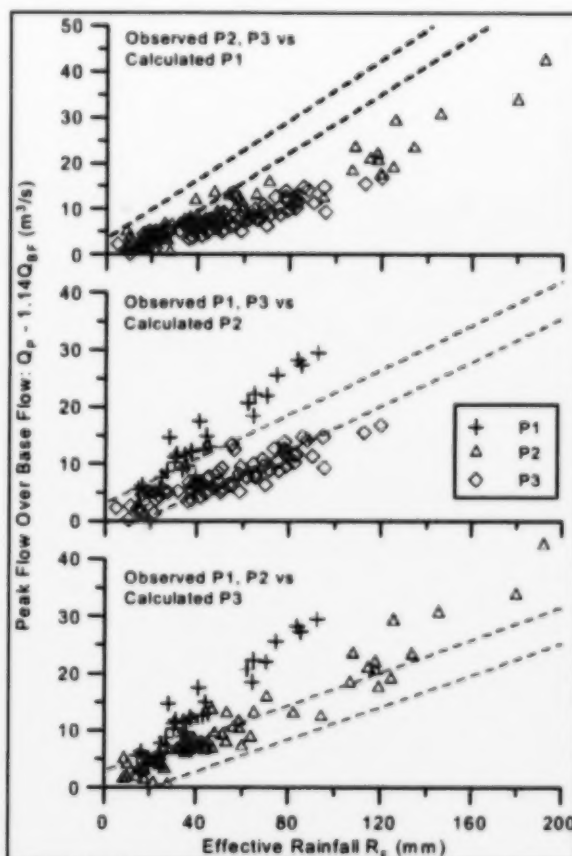


Figure 11. Graph to determine if a change in peak flow is significantly affected by ECA. To be affected, an observed peak flow (symbols) must be outside the prediction limits (dashed lines) of the period to which it is being compared.

The difference between the actual ECA and the mean ECA corresponding to each model equation (ΔECA) was also calculated for each storm (Appendix C). The ECA that was used depended on event type. For the rain-on-snow events, ΔECA was calculated using the ECA for the rain-on-snow zone; for the rain-only events, the overall ECA for the whole Russell Creek watershed was used.

The outcome of this application of the peak flow model is a direct comparison between actual peak flows under ECA conditions that exist at the time of the storm in question, and expected peak flows based on other ECA conditions that are known to have occurred at Russell Creek. The percent difference between observed and expected peak flows can then be assumed to be related to the difference in ECA between the prevailing condition and the ECA condition represented by the model equation. Below a peak flow of about 9–10 m³/s, it is difficult to observe a change in peak flow between time periods (Figure 9): the data points are clumped together and the error

bands all overlap. However, based on relative changes in peak flow and ECA above a peak flow of 9 m³/s, a logarithmic relationship is suggested (Figure 12, lower graph). The graph also suggests that there may be different relationships for rain and rain-on-snow events. From the same data, it is also apparent that the change in peak flow decreases as the size of the peak flow increases (Figure 12, upper graph). This trend is more pronounced for larger changes in ECA; that is, there is an apparent interaction between the magnitude of the expected flow change and the storm size. This interaction may be used to adjust the expected change in peak flow to a logarithmic relationship with ECA that is independent of storm size.

To perform the adjustment discussed above, for each of the DQ_p ranges shown (Figure 12, upper graph) a linear regression equation was used to "de-trend" the data—that is, the slope of the relationship was removed while maintaining the mean of each data range. At the same time, all "unaffected" peak flow comparisons were also removed from the data set. The remaining data form a logarithmic relationship with ΔECA (Figure 13, lower graph):

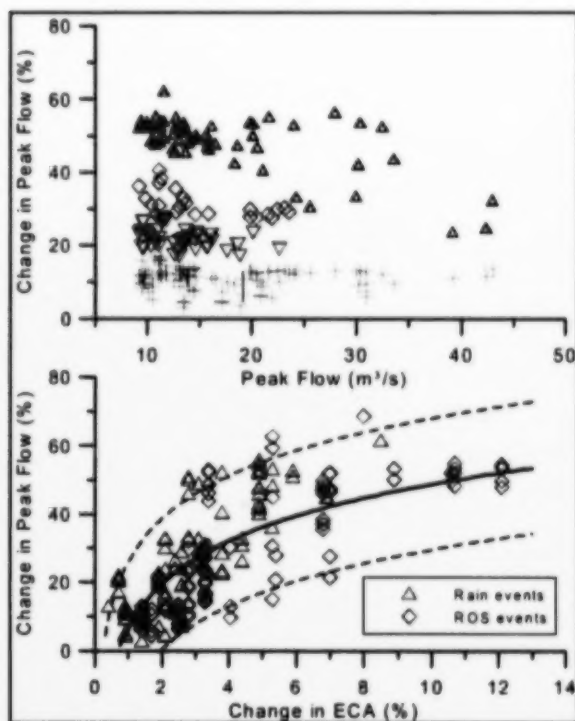


Figure 12. Relationship between change in peak flow and change in ECA (lower graph) at Russell Creek, 1991–2001. A logarithmic relationship is fitted to the lumped data (solid line) and the dashed lines represent a 90% prediction interval. These data points are "unadjusted". The change in peak flow also decreases as the peak flow increases (upper graph), with different relationships for different ranges of ΔECA as represented by the different symbols. This can be used to adjust the ΔQ_p data to make them independent of peak flow.

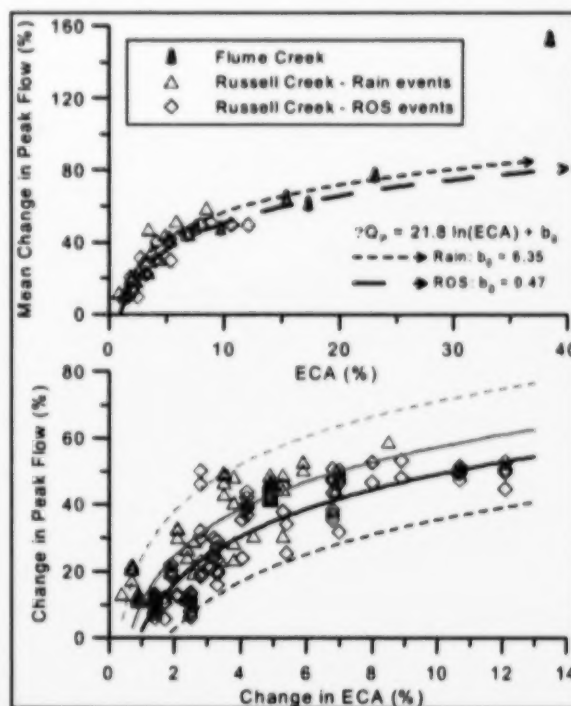


Figure 13. The ΔQ_p data when adjusted for peak flow and with the "unaffected" events removed are a function of the logarithm of ΔECA and event type. The data from Flume Creek represent the mean of all large events (including the unaffected ones). Although not a valid comparison, it suggests that the logarithmic function might be generally applicable.

$$\Delta Q_p = 10.3 + 20.4 \cdot \ln(\Delta ECA) - 8.19 \cdot T \quad (11)$$

where,

T is the event type as before.

This equation has an R^2 of 73.5% and a standard error of 8.148. All terms in this equation are significant at more than 99% confidence, however the effect of event type may be a result of calculating the ΔECA values from ECAs within the rain-on-snow zone separately from the rest of the watershed. This resulted in two 90% prediction limits, one for each event type. For readability, only the upper limit from the rain events and the lower limit from the rain-on-snow events were plotted on Figure 12 (lower). This relationship indicates a change in peak flow of $49\% \pm 13\%$, for a 10% change in ECA. At a 5% change in ECA, the change in peak flow is $35\% \pm 13\%$.

As discussed above, the relative changes in peak flow are not always significant with respect to a given ECA difference. This does not mean that the event in question has not been affected by harvesting, only that the model is not able to detect a significant change in peak flow that could be attributed to the ECA difference that is represented by the equation being used. The model is based on 165 events; 335 comparisons were made using this model, of which 133 (40%) were considered unaffected by harvesting because they were not outside the prediction limit of the equation used for the comparison. Conversely, 74% of peak flow changes based on rain-on-snow events and 53% of those based on rainfall events were affected by the corresponding ECA changes (Table 5).

A similar approach was used to examine peak flow changes at Flume Creek (Roberts Creek Study Forest, Sunshine Coast) (Hudson 2001a). The Flume Creek study follows the classic paired watershed approach where changes in peak flow were observed as a result of the application of two alternative silvicultural treatments. A strip retention treatment was applied at F5 (61 ha) and a variable retention treatment at F4 (39 ha). The treatments were applied in two stages, such that during the first year after harvesting the canopy removal was about half of the target cut. Regression equations were constructed relating peak flows on each treatment unit to matched flows on the unharvested control (F6) using pre-treatment data. These equations, based on 38 matched peak flow pairs on F5 and 28 on F4, constituted the model by which to assess relative changes in peak flow due to the treatments. Any flow peaks that fell outside the prediction limit of the pre-treatment regressions were deemed to have been altered by harvesting. Among the flows affected by harvesting, mean flow changes of up to 200% at 38% canopy removal were reported.

For comparison with the changes reported here for Russell Creek, the data were re-analyzed (Table 5). For the purpose of this analysis, an additional regression was performed relating peak flows on the treated units to the unharvested control in their state after Year 1. This provided the means to assess the change in peak flows between two harvested states, and allowed for some overlap with the Russell Creek data. As with the Russell Creek data, if a peak flow was not affected by harvesting, it was

assigned a value of 0% change relative to the control watershed. If the peak flow in question was affected by harvesting, the percent change was calculated by expressing the difference between the observed flow and the flow predicted by the pre-treatment regression as a percentage of the pre-treatment flow. However, this time the mean change in all flows, including those that were not affected by harvesting, was also calculated for each treatment (Table 5).

The post-treatment periods at Flume Creek consisted of 22 matched pairs in Year 1, and 19 in Year 2-3. Of the Year 1 events, 19 were considered "large" at F5 and 15 at F4. In Year 2-3, only six events on F5 and 9 on F4 were considered large. Thus, Flume Creek results are based on 64 peak flow comparisons, while for Russell Creek there are over five times as many comparisons on which to base the results. At Flume Creek, overall 45% of the "large" treatment peak flow pairs were found to be affected by harvesting, whereas at Russell Creek 60% of the peak flow comparisons were affected by the corresponding ECA difference. Consequently there is a big difference in peak flow response to harvesting depending on how the response is determined.

At both sites, the value of any percentage changes in peak flow that were determined to be "unaffected" was set to zero. For a given ECA change / canopy removal, two mean quantities were calculated: the overall mean peak flow change of all flows including the zeros, and the mean peak flow change of the affected flows only (Table 5). In both cases these were calculated on the "large" flows only, i.e., the flows below a 0.5-year return period were filtered out in advance. The mean of the affected flows was found to be 135% larger than the overall mean at Flume Creek, and 180% larger at Russell Creek. The mean increase in all flows at Flume Creek is comparable to the mean increase in affected flows at Russell Creek (Figure 12, upper graph). The difference between the two sites is likely a result of several factors, including:

- Sample size – Usable sample size at Russell Creek is more than five times that of Flume Creek.
- Scale – Russell Creek drains 61 times as much area as the average of F4 and F5.
- Climatic factors – Russell Creek is in Snow Accumulation Zone 2, whereas Flume Creek is in Zone 4. This is likely to have an effect because of the dominance of rain-on-snow events at both sites.
- Distribution of harvesting, both spatial and temporal – Russell Creek harvesting is distributed in blocks of various stages of regeneration (Table 2), whereas at Flume Creek the treatments were contiguous and all the same age.
- Direction of the change in forest cover – At Russell Creek, observed peak flow changes are the result of recovery from a disturbed state, whereas at Flume Creek, the changes were due to forest canopy removal.

Notwithstanding the above, results from Flume Creek may be compared to the Russell Creek results in an effort to establish a

Table 5. Mean differences in flow and ECA, Flume Creek and Russell Creek.

Area	Canopy removal or change ECA	Mean % change flows >0.5 y Tr		
		All flows	Affected flows	% flows affected
Flume Creek				
Strip Shelterwood Year 1 vs P	9.7	48.0	86.4	55.6
Strip Shelterwood Year 2-3 vs P	17.3	61.6	123.2	50.0
Strip Shelterwood Year 1 vs 2-3	7.6	16.1	48.2	28.6
VR Year 1 vs P	23.1	77.5	232.5	33.3
VR Year 2-3 vs P	38.5	153.0	229.5	66.7
VR Year 1 vs Year 2-3	15.4	65.0	196.4	33.3
Russell Creek, rain-on-snow events, observed minus modeled flows under declining ECA conditions (ECA calculated as a proportion of the 300-800-m elevation band).				
	12.1		49.5	73.5
	10.7		49.7	
	10.6	24.9	49.8	
	8.9		50.7	
	8.9		50.7	
	8.0		49.7	
	7.0	37.2	45.1	
	6.8		44.3	
	5.4	27.8	29.8	
	5.3	7.6	41.8	
	4.2		40.1	
	4.1	19.8	29.7	
	3.3	11.9	22.1	
	3.2	13.5	27.0	
	3.1	11.4	22.8	
	2.8	19.8	31.2	
	2.5	1.0	11.3	
	2.1	2.9	11.7	
	1.9	13.8	20.7	
	1.7	7.2	9.8	
	1.4	8.8	8.9	
Russell Creek, rainfall events, observed minus modeled flows under declining ECA conditions (ECA calculated as a proportion of the whole watershed).				
	8.5		59.0	52.5
	6.9		44.3	
	5.9	51.7	51.7	
	5.3		41.4	
	4.9	44.3	44.3	
	4.4	7.5	30.7	
	3.8	5.7	35.3	
	3.5		47.2	
	3.4	7.7	23.2	
	2.6	8.1	24.3	
	2.4		18.7	
	2.1	8.4	20.3	
	1.9	4.6	19.7	
	1.4	7.2	11.1	
	0.9	4.2	12.2	

process that may result in an understanding of the relationships between changes in peak flow and ECA in Coastal British Columbia (Figure 13, upper graph). Using the mean change in peak flow based on all "large" flow comparisons (Table 5), the following relationship applies to Russell Creek:

$$\Delta Q_p = 21.8 \cdot \ln(ECA) + 6.35 - 5.88T \quad (12)$$

The use of averaged data has resulted in an R^2 of 85.7% and a standard error of 5.3% for this relationship. The graph shows that Flume Creek data based on the average of all "large" peak flows is comparable to Russell Creek data for affected large peak flows. The data point for Flume Creek under the variable retention treatment at 38% canopy removal represents a departure from this because it is dominated by some very large rain-on-snow events that were increased over pre-treatment levels by more than 230%.

5. DISCUSSION

Results presented here are comparable to results of Jones and Grant (1996) and Thomas and Megahan (1998) in the following ways:

- There is a detectable increase in peak flow that apparently diminishes as the size of the storm (and hence, the peak flow) increases. (See the upper graph of Figure 12; this trend has been removed in the model to yield a relationship that is independent of storm size within the range of conditions studied.)
- Relative changes in peak flow are apparently large for relatively small changes in ECA, but the variability is also quite large. For example, a change in ECA of only 5% implies a change in peak flow of anywhere from 22 to 48%; if ECA changes by 10%, the peak flow change may be anywhere from 37 to 63%. These changes are comparable to those detected by Jones and Grant (1996) for large basins; they found a 30 to 55% increase in peak flow for one basin for a 5% change in cut.

However, unlike other analyses (Jones and Grant, Harr, etc.) this analysis is unique in many ways:

- Results are not based on a paired watershed analysis, but instead a rainfall-peak flow model that was developed for Russell Creek is used.
- Contrary to the Jones and Grant results, the changes that occurred at Russell Creek were not related to roads. The road network has remained relatively unchanged from 1991 to present, except for routine maintenance.
- The high variability in peak flow response due to rain-on-snow conditions that has typically plagued studies of peak flow response to rainfall has been significantly reduced by using a derived rainfall parameter that incorporates a factor to adjust for the additional water yield that occurs during ROS conditions. Although the rain-on-snow adjustment factor is entirely empirical it is in the same range as other more physically based analyses (see **Appendix D**).
- Typically, studies have examined the increases in peak flows after applying harvesting treatments to creeks, but have not

reported systematically on the subsequent decrease in peak flows as a new forest regenerates.

- While Thomas and Megahan claimed not to be able to detect a change in peak flow for a 2-year event, this study has detected changes in peak flow throughout the range of flows represented by the period of the study.

Despite the uniqueness of the result, the decline in peak flows from 1991 to present is real. Because peak flow is related to basin-average effective rainfall (which is a composite variable), rather than to rainfall at an index site, it is a challenge to find events that resulted from directly comparable meteorological conditions at different ECA levels. Events that occurred on 10/31/92 and 10/15/95 are close (**Figure 14**). Both are rain-on-snow events. **Table 6** summarizes the relevant quantities of each event.

A change in ECA of 7.8%, resulted in a change in the difference between the base flow and peak flow of 4.74 m³/s. This represents a change in peak flow of 28.5% expressed as a ratio of the average of the two peak flows.

The separation of rainfall and rain-on-snow events resulted in two different equations to predict changes in peak streamflow (Equations 11 and 12; **Figure 13**). It is important to be aware that the equation for rain-on-snow events is based on ECA within the rain-on-snow zone, which is higher than overall basin ECA. This will usually be the case since typical coastal watersheds tend to have around 60% of their area in the rain-on-snow zone, with harvesting concentrated there. Thus, ECA within the rain-on-snow zone is usually higher than basin-wide ECA across all three zones (in Russell Creek it is around 50% higher). For this reason, there is little difference which curve in **Figure 13** is used because most of the difference between the curves is due to the difference in ECA between the rain-on-snow zone and the whole watershed. It is important to be aware of this distinction when applying these results.

Although the peak flow model accounts for rain-on-snow conditions using an adjustment (ROV_{adj}), it is still logical to divide up the events in this way. Results show that peak flows from rain-on-snow events, are more likely to be affected by harvesting than those generated by rainfall. Variability of the peak flow response to ECA changes is greater among rain-on-snow events than among rainfall events both at Russell Creek (regressing ΔQ_p against ΔECA for rain-on-snow events results in a standard error of 7.8%; for rainfall events the standard error is 6.8%) and elsewhere (Hudson 2001a). This helps to substantiate the assumption that the rain-on-snow zone is more sensitive than other zones to changes in peak flow, and therefore in many cases it may be warranted to examine the rain-on-snow zone separately from other elevation bands in a watershed.

5.1. Implied Changes to Flow Frequency

The effect of increased peak flow on flood forecasting can be seen easily. Linsley et al. (1982) recommend using Weibull's return interval, which gives the largest peak flow (43.0 m³/s on 07 November 1995) a return interval of $n+1$ years, where n is the length of record. The peak flows were separated into rain

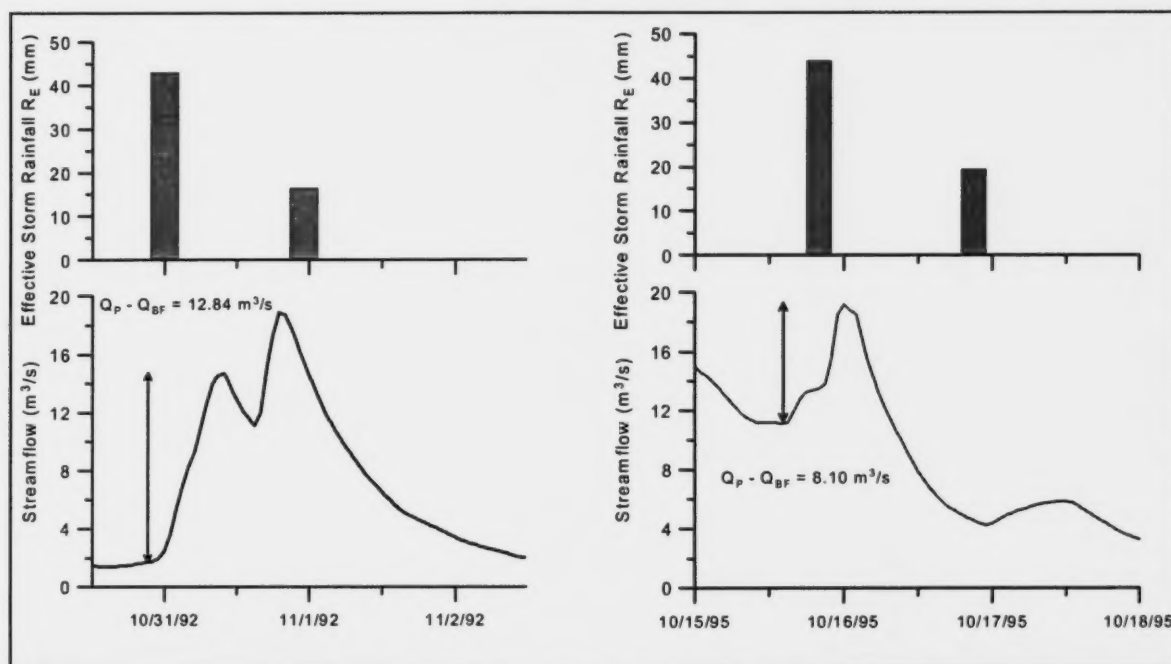


Figure 14. Two rain-on-snow-driven events at Russell Creek from different periods with comparable R_E . The difference in peak flow response between the two events clearly illustrates the effect of the difference in ECA between the two periods. For the 31 October 1992 event, the ECA of the rain-on-snow zone was 32.8%. For the 15 October 1995 event it was 25.0%. Thus, for an ECA difference of 7.8%, the change in the difference between the base flow and peak flow was 4.74 m^3/s . This represents a change in peak flow of 28.5% expressed as an average of the two peak flows.

Table 6. Summary of relevant quantities for two events.

Date	Q_{BF} (m^3/s)	Q_P (m^3/s)	$Q_P - Q_{BF}$ (m^3/s)	ECA (%)	R_{SN}	ROS_{adj}	R_E
31-Oct-92	1.865	14.700	12.835	32.8	33.922	9.139	43.061
15-Oct-95	11.100	19.200	8.100	25.0	22.783	21.199	43.982

events and rain-on-snow-driven events and then ranked. Because the rain-on-snow-driven peaks were all larger than the rain events, they were chosen to form the series of annual peak flows (Table 7). This series formed a logarithmic distribution (Figure 15). Equation 12 suggests that flows in the range of 1 to 2 year return interval have been increased by an average of 70% due to harvesting.

Results show that the flow regime of Russell Creek has been altered by harvesting and apparently remains in a state of change as ECA declines with forest regeneration. This causes uncertainty in defining flows of a given return period. The effects of this scenario on engineered structures are two-fold. If structures are designed based on enhanced flows, then the structures might be over-designed. However, a more serious outcome is that if bridges and culverts are designed based on flows

from unharvested creeks, then they may be under-designed with respect to flows that are likely to occur once the harvesting has been carried out.

5.2. Geomorphic Implications

The increases in peak flow implied by these results suggest that sediment transport processes may have been accelerated as a result of harvesting (Hudson 2001c). Sediment budget studies at Russell Creek have found that a peak flow of about $10 \text{ m}^3/\text{s}$ is a threshold above which sediment transport processes start to operate (Hudson and Sterling 1998). According to the flood frequency analysis that is reported above, the 1.36-year event has a peak flow of $10 \text{ m}^3/\text{s}$ when Equation 12 is used to remove the effects of ECA on peak flows. The commonly held view is that bankfull discharge represents the main channel-forming flow in an equilibrium, alluvial channel (Wolman and Miller 1960). The return period of bankfull discharge is generally assumed to be about 1 to 2 years.

The ECA conditions in Russell Creek have boosted the peak flow of the 1.36-year event to about $17 \text{ m}^3/\text{s}$. Under current conditions in the watershed, the $10 \text{ m}^3/\text{s}$ peak flow event now has a return interval of 0.78 years. This implies that sediment transport processes operate 74% more frequently than they

Table 7. Annual series of rain-on-snow-driven flow events.

Year	Q _p measured (m ³ /s)	Rank	Tr (y)	ECA in ROS (%)	% increase in peak flow	Q _p at 15% ECA (m ³ /s)	Q _p at 0% ECA (m ³ /s)
1995	43.000	1	12.0	25.0	70.6	28.540	25.199
1995	39.203	2	6.0	25.0	70.6	26.020	22.974
1993	30.900	3	4.0	28.9	73.8	19.576	17.779
1995	25.600	4	3.0	25.0	70.6	16.991	15.002
1992	21.600	5	2.4	32.8	76.6	15.512	12.269
2001	20.187	6	2.0	18.9	64.5	13.897	12.234
1999	19.901	7	1.7	22.1	68.0	13.232	11.849
1998	18.693	8	1.5	24.2	69.9	12.558	11.000
1997	16.203	9	1.3	25.6	71.2	11.625	9.576
1998	15.964	10	1.2	24.2	69.9	10.725	9.467
2000	15.906	11	1.1	20.3	66.1	10.665	9.394

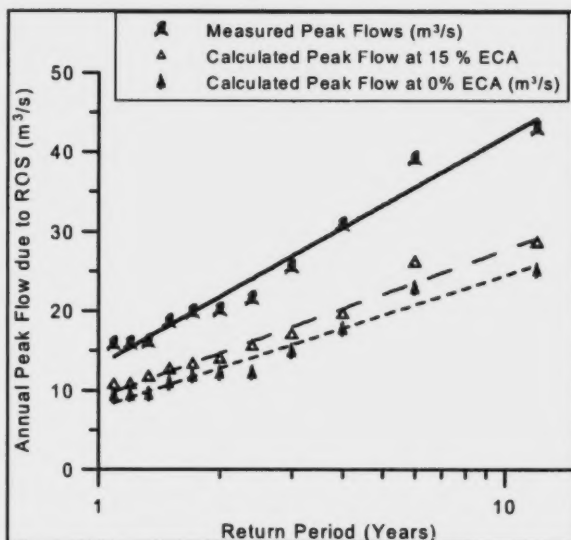


Figure 15. Annual peak flow under three scenarios: measured flows, and calculated flows adjusted to two reference ECA levels (15% and 0%). Based on ECA calculated for the rain-on-snow zone only.

would have prior to harvesting, and that flows of a given return interval have increased by 70%. Thus, harvesting at Russell Creek has resulted in a significant increase in the frequency of events capable of altering the stream channel. As a result, it is reasonable to expect that channel erosion and scour processes have been accelerated by the condition of the forest cover.

For the east coast of Vancouver Island, a large storm is com-

monly defined as one that exceeds 60 mm of rain in 24 hours, and a medium storm as one exceeding 30 mm in 12 hours. Based on peak flows and storm rainfall data from period 1, the 30-mm storm threshold is associated with a peak flow of 14.1 m³/s, and a large 60-mm storm with a peak flow of 22.8 m³/s. These events had return periods of about 1.1 and 2.2 years respectively (Table 8). Therefore, these storm thresholds are significant because they encompass the commonly accepted return period of the bankfull discharge. At an ECA of 15% within the rain-on-snow zone (i.e., current conditions) the 1.1- and 2-year flows are expected to be about 10 and 15 m³/s respectively. Thus, peak flows in the range of 10–20 m³/s are in some ways the most important at Russell Creek because they:

- are associated with sediment transport and channel forming processes,
- have been altered by harvesting, and
- are decreasing in frequency and duration as ECA declines.

An analysis of storm frequencies in Russell Creek shows that there is a slight decline in the annual mean occurrence of medium and large storms from Period P1 to Period P3. There is considerable fluctuation in storm frequency within each period. The increased mean duration of exceedence of the 10 m³/s peak flow in Period P2 reflects the large number of storms in the 1995–96 water year (there were seven medium and six large storms). The occurrence of the 15 m³/s peak flow event has declined from Period P1 to present, whereas the 20 m³/s threshold has not been exceeded in Period P3 (Figure 16).

As an example, the 1995–96 water year contained the four largest peak flows, all resulting from rain-on-snow. The 10-, 15-, and 20-m³/s peak flows were exceeded twelve, twelve, and seven times respectively for a total of 511 hours of flow over 10 m³/s (Figure 17). In contrast, in 1998–99 there were twelve medium and three large storms. The 10-, 15-, and 20-m³/s peak flows

were exceeded eleven, two, and zero times respectively for a total of 140 hours of flow over $10 \text{ m}^3/\text{s}$ (Figure 17). The frequency and duration of flows $>10 \text{ m}^3/\text{s}$ has declined compared to 1995–96 despite an increase in frequency of medium storms. There are fewer large storms, but this is not sufficient to explain the decline in high flows.

Table 8. Peak Flows of various return intervals, calculated by annual series for current and pre-harvesting conditions. Based on ECA calculated for the rain-on-snow zone.

Tr (y)	Q_p		
	Current (m^3/s)	15% ECA (m^3/s)	0% ECA (m^3/s)
2.15	22.68	15.270	13.32
2.00	21.78	14.688	12.80
1.50	18.18	12.371	10.72
1.40	17.32	11.815	10.22
1.36	16.95	11.582	10.01
1.20	15.39	10.573	9.10
1.10	14.30	9.873	8.47
0.90	11.79	8.256	7.02
0.78	10.00	7.104	5.98
0.60	6.72	4.991	4.08
0.50	4.44	3.522	2.76

The above storm and flow frequency analysis demonstrates the importance of the changes in peak flow that the model has revealed in terms of their effect on geomorphically significant flows.

5.3. Evidence of Channel Change

Water Survey of Canada collected 27 measurements of streamflow by current metering between November 1991 and the end of 1999 (Figure 18). Based on these measurements it is apparent that a major shift in gauge height occurred in the fall of 1995. This shift most likely occurred between the 08 and 17 November in response to events with peak flows of 43.0 and $42.4 \text{ m}^3/\text{s}$ respectively, the largest peak flows recorded at Russell Creek (Appendix B and Table 6). The drop in gauge height for a given flow suggests lowering of the bed due to channel erosion, which is consistent with extreme peak flows. Equation 12 indicates that the peak flows of those events were boosted from about $25 \text{ m}^3/\text{s}$.

This shift in gauge height has been noted by Hudson and Fraser (2002). It appears that the channel bed was lowered by about 0.5 m (Figure 18). The shift was permanent; rating curves that have been in effect since then indicate that the channel is recovering gradually over time. It is estimated that about 0.15 m of recovery has occurred in the 6.5 years since the channel scour occurred. At that rate, full recovery is likely to take about 20 years.

One possible explanation for the gauge height shift is that the entire reach containing the gauging site has been degraded. The gradual recovery would then be consistent with transport of gravel back into the reach. The following disturbance indica-

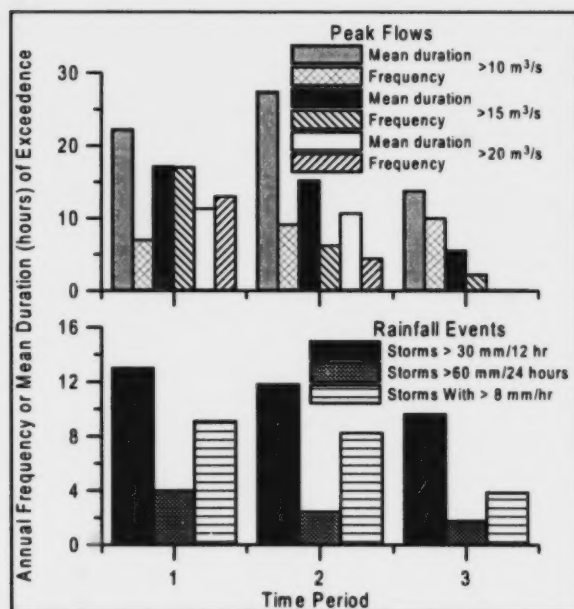


Figure 16. Frequency of "medium" and "large" storms at Russell Main.

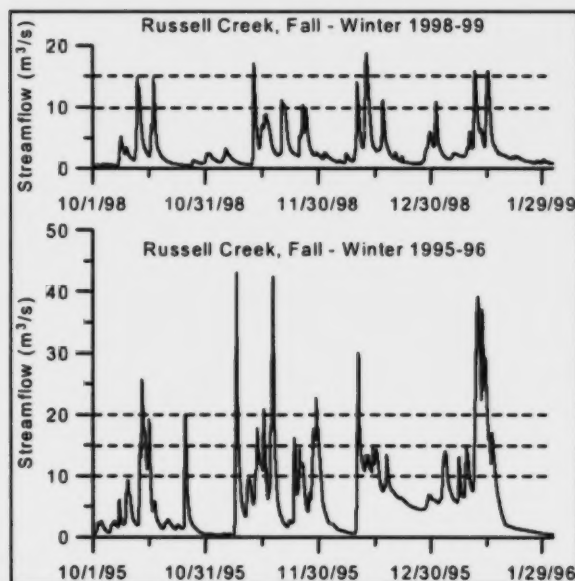


Figure 17. Frequency of exceedence of geomorphically significant streamflow thresholds at Russell Creek.

tors are typical of degraded channels, many of which can be seen on the accompanying photos:

- The channel bed is composed primarily of cobbles, although there is evidence of gravel moving back into the reach.
- The riffle-pool structure has partially broken down. Riffles are coarse textured. Pools make up one quarter to one third of the channel length. Pool depth is about 0.5 to 0.75 m (Figure 19).
- There are abandoned back-channels and gravel bars that are becoming colonized with riparian vegetation. There is evidence that the channel is starting to re-establish side channels through some gravel bars at high flow. (Figure 20)
- LWD is present but not functioning. Pieces are either parallel to the banks, or are suspended above the bank and do not contact the water surface even at high flow (Figure 20).

Hudson and Fraser (2002) have noted that the channel is tending towards stability after disturbance. However, there are other possible explanations for the gauge height shift including channel widening or alteration of a downstream control such as the breakup of a debris jam or lowering of a riffle crest. The fact that the rating curves converge at the high end suggests that the channel change is local. Thus, while there is evidence to suggest that the channel is degraded as a result of an increase in peak flows after harvesting, this cannot be fully supported at this time with the available evidence.

6. CONCLUSIONS

The issue of whether or not forest harvesting affects peak streamflows in Coastal British Columbia watersheds has been the subject of recent debate in the literature. In British Columbia, we use equivalent clearcut area (ECA) as an estimate of the potential for existing forest harvesting and regeneration to affect peak streamflow, but the link between ECA and peak streamflow has not yet been developed. This report works towards establishing that link, and also suggests the geomorphic significance of the changes in peak flow.

At Russell Creek, a fourth-order tributary sub-basin of the Tsitika River on northeastern Vancouver Island, a model of peak flow based on rainfall intensity was developed and used to demonstrate a decline in peak flows concurrent with a decline in ECA. The model divides up the 10-year data record into three distinct time periods with significantly different peak flow responses, such that the changes in peak flow can be assessed as a logarithmic function of a relative change in ECA.

These results represent an important advancement in understanding the linkages between forest harvesting, regeneration and peak streamflow. Most studies that have been designed to test the effects of harvesting on peak streamflow have focussed on changes in streamflow after harvesting, but the decline in peak flows that occurs concurrently with hydrologic recovery is just as important as the increase that accompanies harvesting. However, few studies have examined declining peak flows in relation to the re-growth of forest cover.

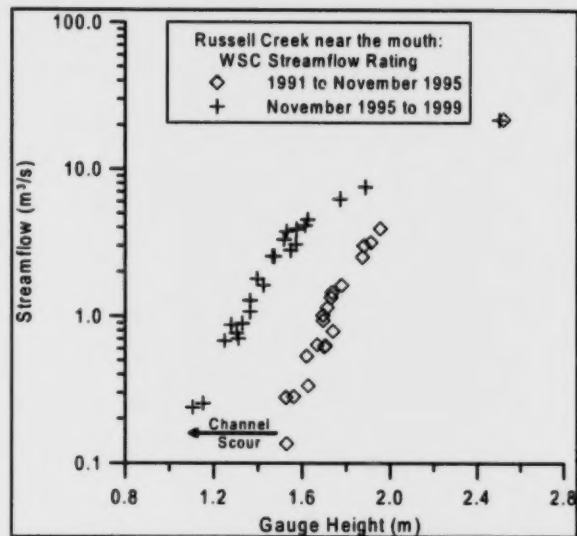


Figure 18. Stream gauging data collected by WSC from 1991 to 1999 clearly show the drop in the channel bed, indicating channel scour associated with ECA enhanced peak flows in November 1995.



Figure 19. Russell Creek control reach. This reach suggests a partial breakdown of the riffle pool structure consistent with channel degradation.



Figure 20. Russell Creek, looking downstream at the gauging control reach, which shows some features typical of degrading channels.

The changes in peak flow that were observed as the ECA in the watershed declined may seem excessive; the logarithmic relationship between DQ_p and DECA suggest that if ECA changes by 4%, there is a 25% change in peak flow. A 10% change in ECA implies a 40% change in peak flow. However, in spite of the non-standard method used, the results are closely comparable to results obtained at Flume Creek, where the standard paired watershed approach was used.

The difference between the two curves of change in peak flow as a function of ECA (Figure 9) suggests that the difference may be due to differences in scale between the sites. That is, the difference in response between the two sites suggests that the magnitude of the observed change in peak flow for a given change in ECA is inversely proportional to watershed area. However, because there is no overlap in ECA range between the two studies, there are many potential questions that cannot be answered at this time:

- How does the ECA range of the data affect the outcome? That is, it is possible that the relative changes in peak flow are specific to the narrow ECA range under which the study has been carried out.

- In order to put the two data sets together, it is necessary to assume that a change in ECA has the same effect as new harvesting on peak flows. For example, a change in ECA from 15 to 25% would have to result in an increase in peak flow equivalent to a 10% cut.

- Flume Creek is in Snow Accumulation Zone 4, whereas Russell Creek is in Zone 2. This may be a factor that affects the peak flow response to ECA changes.

- Before the results from this project can be generalized, the method would have to be tested in other watersheds with a broader range of morphological characteristics.

These results represent a step towards establishing the link between ECA and streamflow. The peak flow modeling approach is particularly useful because it can be applied in watersheds without an un-harvested control. It can be repeated in any watershed with a suitable data record. Therefore, that should be the next step in linking changes in peak flow to ECA.

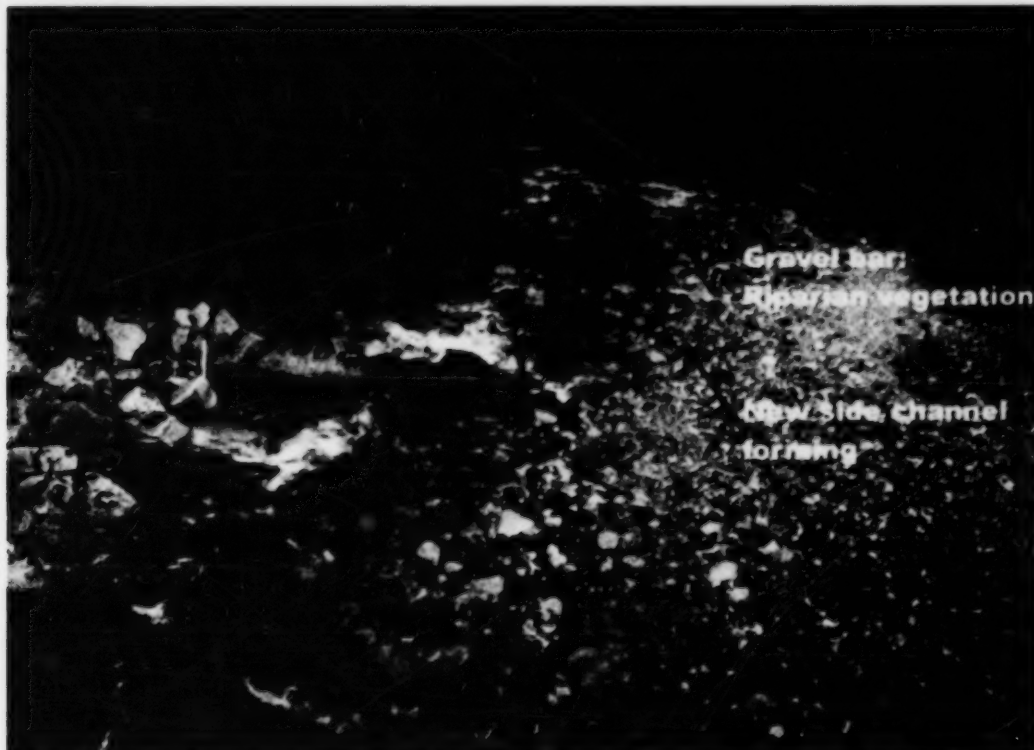


Figure 20. Russell Creek, looking downstream at the gauging control reach, which shows some features typical of degrading channels.

The changes in peak flow that were observed as the ECA in the watershed declined may seem excessive; the logarithmic relationship between DQ_p and DECA suggest that if ECA changes by 4%, there is a 25% change in peak flow. A 10% change in ECA implies a 40% change in peak flow. However, in spite of the non-standard method used, the results are closely comparable to results obtained at Flume Creek, where the standard paired watershed approach was used.

The difference between the two curves of change in peak flow as a function of ECA (Figure 9) suggests that the difference may be due to differences in scale between the sites. That is, the difference in response between the two sites suggests that the magnitude of the observed change in peak flow for a given change in ECA is inversely proportional to watershed area. However, because there is no overlap in ECA range between the two studies, there are many potential questions that cannot be answered at this time:

- How does the ECA range of the data affect the outcome? That is, it is possible that the relative changes in peak flow are specific to the narrow ECA range under which the study has been carried out.

- In order to put the two data sets together, it is necessary to assume that a change in ECA has the same effect as new harvesting on peak flows. For example, a change in ECA from 15 to 25% would have to result in an increase in peak flow equivalent to a 10% cut.

- Flume Creek is in Snow Accumulation Zone 4, whereas Russell Creek is in Zone 2. This may be a factor that affects the peak flow response to ECA changes.

- Before the results from this project can be generalized, the method would have to be tested in other watersheds with a broader range of morphological characteristics.

These results represent a step towards establishing the link between ECA and streamflow. The peak flow modeling approach is particularly useful because it can be applied in watersheds without an un-harvested control. It can be repeated in any watershed with a suitable data record. Therefore, that should be the next step in linking changes in peak flow to ECA.

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APPENDIX A: EXAMPLE CALCULATIONS OF BASIN-AVERAGE RAINFALL

Table A-1. Measured precipitation parameters and calculated basin-average rainfall.

Start date & time	Site	Storm Rs (mm)	Duration (h)	Maximum intensities (mm/internal)				
				1 h	3 h	6 h	12 h	24 h
19-Nov-98	Russell Main	12.0	3.0	6.0	13.0	18.0	27.0	41.0
	Upper Russell	6.0	2.0	5.0	8.0	18.0	25.0	36.0
	Upper Stephanie	11.0	11.0	8.6	11.0	27.4	38.1	49.7
	Basin average	12.9		9.7	11.4	29.2	40.7	50.7
09-Dec-98	Russell Main	63.0	34.0	6.0	16.0	29.0	42.0	73.0
	Upper Russell	64.5	NA	NA	NA	NA	NA	NA
	Upper Stephanie	62.2	35.0	8.7	17.0	29.4	48.4	59.6
	Basin average	38.8		5.9	11.8	20.4	33.3	42.0

Table A-2. Example calculations of 24-h maximum storm rainfall intensity (R_{24}) for two storms.

Start date & time	Mean daily temp.			Precipitation distribution gradients						Max. 24-h intensity		
	Mean daily lapse (°C/100 m)	Russell, elev. 275 m (°C)	Stephanie, elev. 830 m (°C)	Tc elev. (m)	0°C elev. (m)	Grad1*	Grad2*	Int. 1*	Int. 2*	Russell Main, elev. 275 m (mm)	Upper Russell, elev. 490 m (mm)	Stephanie, elev. 830 m (mm)
11/19/98 0:00	-0.2276	3.3	2.0	842.8	1721.6	-0.0233	0.0637	47	16	41	36	49.7
12/09/98 0:00	-0.2703	3.0	1.5	645.0	1385.0	-0.1011	0.0388	101	39	73	51.3	59.6
Band	19-Nov-98 storm								09-Dec-98 storm			
	Mid-point elev. (m)	Area (km²)	Mean daily Temp. (°C)	Temp. factor	Band precip.	Band rainfall	Area weighted rainfall	Mean daily Temp. (°C)	Temp. factor	Band precip.	Band rainfall	Area weighted rainfall
B1	282	0.060	3.28	1.000	40.8	3.28	1.000	2.98	1.000	72.3	72.29	4.34
B2	350	1.052	3.13	1.000	39.3	40.8	3.13	2.80	1.000	65.4	65.41	68.82
B3	450	3.488	2.90	1.000	36.9	1.000	39.3	2.53	1.000	55.3	55.30	192.90
B4	550	4.263	2.67	1.000	51.3	51.30	218.71	2.26	1.000	60.6	60.58	258.25
B5	650	2.715	2.45	1.000	57.7	57.67	156.60	1.99	0.993	64.5	64.02	173.83
B6	750	3.122	2.22	1.000	64.0	64.05	199.95	1.72	0.858	68.3	58.64	183.07
B7	850	2.933	1.99	0.992	70.4	69.84	204.83	1.45	0.723	72.2	52.21	153.13
B8	950	2.135	1.76	0.878	76.8	67.42	143.93	1.18	0.588	76.1	44.73	95.50
B9	1050	2.085	1.54	0.764	83.2	63.56	132.52	0.91	0.453	80.0	36.21	75.49
B10	1150	2.276	1.31	0.650	83.2	54.09	123.11	0.64	0.318	80.0	25.40	57.81
B11	1250	1.815	1.08	0.537	83.2	44.63	80.99	0.36	0.182	80.0	14.59	26.48
B12	1350	1.856	0.85	0.423	83.2	35.16	65.27	0.09	0.047	80.0	3.78	7.02
B13	1450	1.912	0.63	0.309	83.2	25.70	49.14	-0.18	0.000	80.0	0.00	0.00
B14	1550	1.016	0.40	0.195	83.2	16.24	16.49	-0.45	0.000	80.0	0.00	0.00
B15	1650	0.153	0.17	0.081	83.2	6.77	1.03	-0.72	0.000	80.0	0.00	0.00
		30.88					50.68					41.99

^a Grad1 and Int1 are the slope and intercept of the precipitation-elevation relationship between Russell Main and Upper Russell.^b Grad2 and Int 2 are for the precipitation-elevation relationship between Upper Russell and Upper Stephanie.

APPENDIX B: A LIST OF STORM PARAMETERS USED TO BUILD A PEAK FLOW MODEL FOR RUSSELL CREEK

Storm date	Basin average storm event rainfall parameters						Flow parameters				
	Total event volume (R _t) (mm)	Storm Duration Class (D) (mm)	Peak storm rainfall intensity of stated duration					Base flow Q _{BF} (m ³ /s)	Peak flow Q _p (m ³ /s)	Time to peak T _p (h)	Event type (T)
			1-h (R ₁) (mm)	3-h (R ₃) (mm)	6-h (R ₆) (mm)	12-h (R ₁₂) (mm)	24-h (R ₂₄) (mm)				
07-Nov-91	30.5	3	3.0	8.2	14.9	22.2	29.5	0.897	11.300	15.0	0
11-Nov-91	38.0	3	3.4	9.4	17.3	26.3	35.2	0.967	13.200	12.0	0
15-Nov-91	62.5	4	4.7	12.7	24.2	38.8	52.7	0.880	21.700	21.0	0
19-Nov-91	93.0	4	6.2	17.0	33.3	54.8	75.0	2.690	32.500	11.0	0
24-Nov-91	34.8	3	3.2	8.8	16.2	24.5	32.7	2.000	13.900	8.5	0
03-Dec-91	35.4	1	7.8	16.3	25.9	31.4	49.4	2.520	12.500	29.0	0
05-Dec-91	45.8	3	3.5	8.7	17.5	28.2	38.8	4.750	18.400	14.0	0
08-Dec-91	43.8	1	9.1	22.4	33.8	40.3	58.0	5.410	21.100	11.0	0
25-Dec-91	70.8	5	4.0	10.5	22.5	38.8	56.3	1.860	24.100	26.5	0
01-Jan-92	84.1	5	6.6	16.4	30.5	48.6	68.9	1.930	30.400	26.5	0
09-Jan-92	85.4	4	8.2	18.0	32.7	54.1	83.9	0.619	28.000	32.0	0
15-Jan-92	28.5	3	3.2	7.3	12.5	22.1	31.1	1.710	16.600	30.0	1
23-Jan-92	33.8	3	4.5	10.5	18.2	25.6	35.7	2.750	20.600	29.0	1
27-Jan-92	8.3	2	2.3	4.4	6.4	7.9	14.1	7.100	13.600	14.0	1
29-Jan-92	74.4	3	8.6	21.3	41.8	63.4	83.0	7.040	33.600	10.0	0
31-Jan-92	24.8	2	4.2	6.9	13.4	21.0	32.2	9.460	22.000	11.0	1
02-Feb-92	65.0	4	5.5	13.3	24.0	42.4	64.0	6.930	30.200	16.5	0
21-Feb-92	23.4	2	3.1	8.4	13.9	21.1	22.7	0.880	12.800	19.0	1
24-Feb-92	14.6	1	3.5	6.7	10.3	13.2	21.5	2.540	8.450	39.0	1
16-Apr-92	27.2	2	3.6	7.2	14.0	21.9	26.2	1.500	10.400	14.0	0
26-Apr-92	22.5	2	4.3	8.0	14.9	19.0	22.3	1.000	10.100	29.0	1
29-Apr-92	23.2	4	1.9	4.2	8.1	13.2	19.5	2.740	8.340	26.0	1
09-Jun-92	42.2	3	3.9	9.7	17.7	27.7	38.6	1.190	9.230	24.0	1
31-Oct-92	33.5	2	5.5	12.4	18.8	28.3	48.4	1.865	14.700	11.5	1
01-Nov-92	6.0	2	0.7	4.0	7.0	11.5	17.1	11.100	18.900	4.0	1
03-Nov-92	37.7	3	3.1	10.5	17.5	24.2	33.0	1.290	13.800	17.5	0
06-Nov-92	64.8	4	3.0	9.2	19.7	37.2	53.2	1.550	20.200	19.5	0
26-Nov-92	24.5	3	2.9	9.0	17.3	24.5	35.6	0.892	8.780	18.5	0
29-Nov-92	32.2	2	2.9	8.9	18.0	27.1	32.2	1.220	8.110	15.0	0
13-Dec-92	38.3	3	7.3	15.0	23.5	32.3	44.4	0.657	8.340	23.0	0
26-Jan-93	56.3	5	5.3	10.6	17.6	26.0	46.9	2.750	11.049	39.0	0
03-Feb-93	3.0	1	0.9	1.4	2.6	3.2	3.7	2.470	5.960	49.0	1
02-Mar-93	52.1	4	2.8	3.0	12.3	24.5	28.9	0.618	13.100	32.0	1
05-Mar-93	30.4	3	3.9	4.7	12.4	21.2	24.2	4.070	13.400	17.0	1
21-Mar-93	75.3	3	6.3	15.9	30.3	49.0	63.7	2.280	21.600	43.0	1
10-May-93	38.3	3	3.9	9.7	15.7	23.4	33.4	1.340	9.610	22.0	0
09-Jun-93	15.3	2	3.1	5.3	11.5	19.2	21.9	0.145	7.947	10.0	1
13-Jun-93	23.0	2	2.4	4.4	8.3	13.9	27.1	1.370	5.680	29.0	0
22-Aug-93	77.5	4	1.5	4.0	15.4	32.8	40.0	0.394	13.500	20.5	0
18-Nov-93	62.6	4	3.9	9.7	19.8	36.2	51.1	0.832	11.171	47.0	0

continued ...

APPENDIX B - continued.

Storm date	Basin average storm event rainfall parameters							Flow parameters			
	Total event volume (R _t) (mm)	Storm Duration Class (D) (mm)	Peak storm rainfall intensity of stated duration					Base flow Q ₉₀ (m ³ /s)	Peak flow Q _p (m ³ /s)	Time to peak T _p (h)	Event type (T)
			1-h (R ₁) (mm)	3-h (R ₃) (mm)	6-h (R ₆) (mm)	12-h (R ₁₂) (mm)	24-h (R ₂₄) (mm)				
22-Jan-94	16.6	2	2.4	5.3	7.3	13.9	18.8	2.810	6.760	27.0	0
27-Feb-94	71.5	4	4.7	15.9	30.3	51.1	58.4	1.160	23.200	15.0	1
01-Mar-94	44.7	4	3.9	12.4	26.1	33.0	51.1	15.700	30.900	10.0	1
01-Mar-94	17.9	2	3.9	6.2	12.5	14.9	44.9	15.700	30.900	10.0	1
12-Mar-94	23.0	5	1.6	3.5	6.3	9.6	16.7	2.180	7.330	36.0	0
01-Apr-94	14.0	2	2.4	4.4	9.4	12.8	14.6	3.570	5.840	28.0	0
10-Apr-94	54.9	4	4.7	8.8	17.7	33.0	44.9	1.950	11.400	15.0	0
18-Oct-94	25.0	3	4.7	6.8	11.6	17.8	24.0	1.080	5.060	14.0	0
24-Oct-94	71.5	2	7.1	22.1	38.6	56.5	65.8	1.390	22.500	15.0	1
25-Oct-94	18.8	2	0.7	9.5	21.6	26.4	33.8	10.900	17.200	5.0	0
30-Oct-94	14.2	2	3.0	6.6	11.7	14.9	34.1	2.270	6.840	11.0	0
21-Dec-94	141.3	6	0.7	10.2	23.7	41.3	70.3	2.690	23.600	29.0	0
07-Jan-95	24.4	1	5.1	10.4	17.9	22.5	37.4	2.770	9.650	11.5	0
28-Jan-95	72.8	3	5.5	15.0	31.3	49.0	59.5	2.680	20.500	13.5	1
31-Jan-95	15.3	1	3.1	6.2	11.5	13.9	21.9	6.390	10.500	8.0	0
02-Feb-95	20.4	1	1.6	4.4	11.5	18.1	18.8	2.810	7.830	11.0	0
20-Feb-95	26.8	2	3.9	11.5	16.7	23.4	23.0	2.410	9.490	12.0	0
23-Feb-95	51.3	4	3.7	9.2	15.7	27.0	39.2	2.510	9.710	12.5	0
08-Mar-95	38.3	3	3.1	8.0	15.7	26.6	31.3	0.521	6.550	16.5	0
14-Mar-95	19.1	3	3.9	8.0	11.5	17.0	19.8	2.560	7.900	13.0	0
01-May-95	15.3	5	3.1	5.3	10.4	14.9	23.0	2.150	5.370	37.0	0
07-Oct-95	22.5	1	4.2	13.1	18.4	23.0	26.4	1.560	6.020	7.0	0
09-Oct-95	46.5	4	0.8	1.5	7.6	19.3	21.8	2.080	9.360	23.0	0
13-Oct-95	135.1	6	2.8	8.9	17.6	30.5	52.6	1.900	25.600	29.0	0
15-Oct-95	16.6	3	6.3	20.4	19.5	28.5	35.5	11.100	19.200	10.0	1
24-Oct-95	67.7	2	0.7	29.6	44.3	56.1	68.9	1.370	19.900	16.0	1
07-Nov-95	125.3	5	6.5	18.1	36.6	53.3	77.2	0.436	43.000	23.0	1
13-Nov-95	25.1	4	1.0	1.2	3.7	5.8	13.3	5.350	17.700	23.5	1
15-Nov-95	13.5	1	6.0	5.6	10.2	11.6	14.7	10.900	20.900	8.0	1
16-Nov-95	113.7	4	6.3	16.7	33.6	57.5	81.6	7.580	42.400	22.0	1
21-Nov-95	21.3	2	0.1	7.6	16.6	19.3	19.6	2.350	16.200	15.0	1
24-Nov-95	38.3	2	4.8	12.7	19.9	34.9	36.0	6.940	14.400	14.0	0
27-Nov-95	32.4	6	1.3	2.2	4.2	10.7	20.8	6.020	22.700	35.0	1
09-Dec-95	132.1	3	14.3	29.1	44.8	59.6	112.9	0.692	30.000	25.0	0
17-Dec-95	3.4	1	6.7	16.0	19.0	20.3	24.8	8.330	13.450	6.0	0
01-Jan-96	6.7	5	2.8	4.7	4.6	10.4	15.2	5.600	14.000	24.0	1
06-Jan-96	43.9	3	8.0	11.7	20.6	29.8	46.2	5.600	13.100	8.0	0
08-Jan-96	8.7	3	1.3	4.0	6.1	10.5	19.1	6.610	14.550	13.0	1
10-Jan-96	91.1	5	10.2	26.4	54.0	95.4	111.4	7.540	39.203	33.0	1
04-Apr-96	152.1	6	5.6	19.0	36.5	57.6	96.7	0.873	24.284	37.0	0
07-Apr-96	17.0	2	2.3	6.5	10.8	16.9	40.0	3.519	9.482	13.0	0
08-Apr-96	24.7	2	1.1	1.1	3.9	11.4	15.4	4.041	5.341	10.0	0
23-Apr-96	21.5	2	1.7	4.1	7.2	20.2	22.7	1.510	6.120	23.0	0
20-Oct-96	20.8	2	3.8	1.0	2.2	8.0	19.9	1.240	11.800	13.0	1
26-Oct-96	12.1	2	2.3	6.5	13.8	23.1	26.4	1.580	13.700	21.0	1
11-Nov-96	8.2	2	0.3	3.1	7.7	8.3	13.9	2.890	5.130	15.0	0
31-Dec-96	43.2	3	3.6	9.3	23.5	32.8	49.4	0.111	7.914	13.0	0

continued ...

APPENDIX B - continued.

Storm date	Basin average storm event rainfall parameters							Flow parameters			
	Total event volume (R _t) (mm)	Storm Duration Class (D) (mm)	Peak storm rainfall intensity of stated duration					Base flow Q _m (m ³ /s)	Peak flow Q _p (m ³ /s)	Time to peak T _p (h)	Event type (T)
			1-h (R ₁) (mm)	3-h (R ₃) (mm)	6-h (R ₆) (mm)	12-h (R ₁₂) (mm)	24-h (R ₂₄) (mm)				
28-Jan-97	43.5	2	6.6	17.6	33.8	42.4	58.4	0.293	9.840	13.0	0
11-Feb-97	6.7	1	2.0	1.9	4.4	7.7	13.5	0.280	5.324	39.0	0
16-Feb-97	15.8	1	3.3	9.6	12.6	18.2	21.5	3.966	5.904	10.0	0
17-Mar-97	64.8	4	4.8	9.8	18.9	35.4	50.4	0.277	7.489	22.0	0
18-Mar-97	14.4	1	3.2	15.6	29.0	41.4	55.8	5.983	7.380	7.0	0
14-Apr-97	10.6	2	6.2	18.2	27.5	33.4	46.4	0.896	7.581	34.0	1
24-Apr-97	11.2	2	6.0	12.3	14.3	12.2	20.7	1.690	7.905	48.0	1
28-May-97	1.5	2	6.1	21.1	31.9	36.8	42.6	3.374	6.870	36.0	0
30-May-97	2.4	2	1.6	4.2	5.2	7.5	21.5	3.101	5.081	11.0	0
16-Jun-97	27.2	2	2.4	8.6	18.7	25.9	23.8	2.167	6.816	18.0	0
18-Jun-97	11.0	1	5.0	11.0	14.0	5.5	10.5	4.165	4.953	9.0	0
27-Jun-97	17.9	1	19.4	21.7	19.2	23.6	22.6	3.082	7.183	9.0	0
07-Jul-97	5.6	2	4.3	8.4	17.4	22.1	32.8	1.273	6.656	12.0	0
26-Aug-97	12.8	2	10.0	0.8	6.4	13.8	22.0	2.021	7.404	10.0	0
16-Sep-97	53.9	4	2.7	4.5	8.6	10.2	41.6	1.062	7.279	27.0	0
25-Sep-97	44.3	4	3.7	15.0	25.7	39.2	44.4	0.291	7.757	23.0	0
27-Sep-97	20.0	3	0.8	4.8	8.8	10.6	14.4	3.102	5.652	13.0	0
29-Sep-97	29.0	2	8.0	13.4	31.0	43.2	40.6	2.028	16.203	13.0	1
01-Oct-97	90.8	4	11.9	28.2	45.6	65.4	95.5	3.349	13.170	9.0	0
03-Oct-97	47.3	3	2.5	5.6	11.2	13.6	35.8	3.867	7.829	12.0	0
09-Oct-97	12.0	1	2.3	6.2	8.3	11.7	21.9	3.148	4.942	36.0	0
15-Oct-97	45.1	5	4.7	11.8	21.1	31.9	59.0	2.369	10.910	17.0	0
24-Oct-97	12.8	3	4.0	1.2	6.3	13.1	19.1	1.500	6.826	12.0	0
28-Oct-97	16.1	2	10.3	7.6	19.0	33.4	45.0	2.104	7.233	11.0	0
29-Oct-97	65.1	2	7.7	19.9	34.0	46.6	70.0	5.501	12.613	18.0	0
02-Nov-97	43.8	6	1.1	3.0	7.5	17.6	37.2	3.673	13.082	20.0	1
05-Nov-97	41.3	5	3.1	8.8	14.3	20.0	33.1	3.349	14.655	21.0	1
22-Nov-97	6.3	6	1.8	3.6	6.1	11.0	32.8	0.372	8.097	28.0	1
12-Dec-97	93.0	4	6.3	13.7	24.5	44.7	75.1	2.049	11.166	21.0	0
27-Dec-97	64.7	6	6.3	2.7	18.3	32.8	45.6	2.927	13.584	29.0	1
17-Jan-98	21.7	3	2.2	12.9	20.2	26.0	37.6	1.627	7.437	14.2	0
11-Feb-98	22.6	4	3.2	9.3	15.4	23.9	30.3	1.150	9.451	17.6	1
18-Feb-98	36.1	2	9.2	22.8	35.2	45.1	52.1	1.908	13.537	7.0	1
11-Mar-98	38.0	3	12.9	20.3	16.0	15.2	15.2	2.719	8.703	17.5	1
12-Oct-98	78.0	5	7.0	17.3	24.8	36.1	54.5	1.145	14.775	22.5	0
16-Oct-98	33.6	1	2.3	12.1	15.7	26.4	57.1	1.842	14.631	12.3	0
11-Nov-98	50.6	4	6.7	17.2	27.4	39.0	48.2	1.036	15.964	22.5	1
14-Nov-98	71.7	2	1.6	5.3	6.9	13.6	15.2	3.184	7.109	17.8	0
15-Nov-98	3.8	3	1.0	2.6	4.7	7.5	16.3	6.479	8.768	14.3	0
19-Nov-98	12.9	2	9.7	11.4	29.2	40.7	50.7	2.326	11.155	6.3	0
09-Dec-98	38.8	5	5.9	11.8	20.4	33.3	42.0	1.142	14.027	22.0	1
12-Dec-98	64.1	3	2.5	13.6	22.1	35.6	57.8	3.463	18.693	17.6	1
15-Dec-98	21.8	1	2.1	7.6	10.8	8.5	4.7	3.887	11.166	8.3	1
27-Dec-98	49.3	6	2.0	5.2	8.6	15.0	26.9	0.861	5.992	54.5	0
30-Dec-98	15.8	1	2.6	7.1	12.3	13.4	15.0	3.370	10.770	12.0	1

continued ...

APPENDIX B - continued.

Storm date	Basin average storm event rainfall parameters							Flow parameters			
	Storm		Peak storm rainfall intensity of stated duration					Base flow Q_{bf} (m ³ /s)	Peak flow Q_p (m ³ /s)	Time to peak T_p (h)	Event type (T)
	Total event volume (R_t) (mm)	Duration Class (D) (mm)	1-h (R_1) (mm)	3-h (R_3) (mm)	6-h (R_6) (mm)	12-h (R_{12}) (mm)	24-h (R_{24}) (mm)				
09-Jan-99	3.4	2	0.5	1.3	2.5	3.7	5.2	3.308	6.030	9.0	0
10-Jan-99	42.7	3	3.1	9.0	19.0	31.4	42.4	3.282	15.800	13.3	1
13-Jan-99	48.3	4	2.7	8.1	16.1	30.7	46.6	3.580	15.700	19.0	1
19-Apr-99	6.7	3	2.9	7.2	10.5	13.9	11.5	4.554	7.780	16.5	0
24-Apr-99	6.5	2	1.3	4.0	7.6	6.5	5.5	5.800	12.745	12.0	1
05-May-99	8.4	4	6.1	17.5	21.3	26.2	20.0	2.161	8.827	23.5	1
30-May-99	6.3	1	5.5	7.1	3.8	7.2	7.0	4.369	11.350	19.0	1
04-Jun-99	17.6	1	3.1	8.7	13.9	15.2	15.2	7.088	10.088	15.0	0
06-Jul-99	48.3	1	28.0	44.3	48.2	50.6	50.6	4.659	10.370	8.3	0
27-Oct-99	52.0	4	5.7	9.4	23.0	33.4	59.4	0.771	10.414	22.3	0
29-Oct-99	56.3	2	4.4	26.7	37.4	47.4	53.9	3.220	9.932	7.0	0
06-Nov-99	48.8	6	3.4	8.0	3.7	9.3	10.8	0.923	8.815	31.7	1
08-Nov-99	77.6	3	13.5	40.1	65.2	95.8	75.9	2.704	19.901	10.5	1
15-Nov-99	34.4	2	12.2	13.0	3.7	12.2	27.8	4.221	12.562	12.8	1
19-Nov-99	55.9	4	2.9	5.3	11.5	22.2	41.2	1.451	5.837	19.5	0
24-Nov-99	16.6	2	1.3	4.7	8.5	12.8	16.4	1.256	6.002	11.0	0
27-Nov-99	8.6	2	3.1	16.2	20.4	8.5	8.9	1.013	6.304	14.0	1
29-Nov-99	63.4	3	2.5	10.0	20.5	40.1	58.5	2.656	8.151	12.3	0
20-May-00	9.5	3	5.2	15.4	28.3	57.2	37.5	2.183	9.207	17.3	0
26-Jul-00	46.1	3	4.0	9.8	23.3	33.2	40.3	0.764	7.392	25.7	0
19-Oct-00	51.9	3	6.6	13.2	22.7	31.2	51.1	1.528	15.906	17.5	1
03-Nov-00	28.4	1	2.5	23.4	34.1	28.5	30.8	1.030	10.854	8.3	1
24-Nov-00	75.9	3	8.8	11.3	26.6	53.2	73.5	0.879	13.721	18.3	0
25-Dec-00	30.0	2	3.6	10.3	19.0	25.6	25.8	1.644	9.572	11.3	1
01-Jan-01	27.6	2	8.4	12.7	24.8	27.6	27.8	1.225	11.297	12.2	1
03-Jan-01	29.9	1	2.5	15.1	20.4	28.9	38.0	4.069	8.376	5.8	0
11-Oct-01	25.9	3	2.1	8.0	15.4	25.7	26.3	0.902	6.263	12.5	0
22-Oct-01	49.7	4	3.6	8.5	13.7	27.6	47.4	1.407	7.399	18.2	0
25-Oct-01	42.1	4	5.3	10.9	21.5	26.3	47.2	0.919	12.787	17.5	1
03-Nov-01	31.8	2	4.5	16.2	26.8	31.9	38.3	0.988	11.611	8.3	1
08-Nov-01	66.2	4	5.4	13.9	27.8	36.8	50.4	2.078	11.636	7.7	0
11-Nov-01	91.9	6	3.1	8.7	16.5	28.4	41.3	1.378	11.187	32.8	1
14-Nov-01	63.7	2	9.1	19.9	36.2	52.9	74.0	4.086	20.187	10.0	1

APPENDIX C: DEVELOPMENT OF THE PEAK FLOW MODEL ^a

Storm date	Observed quantities			Calculated quantities							Differences in peak flow				P1 vs. P2		P2 vs. P3		P1 vs. P3			
	Flow QBF (m ³ /s)	QP (m ³ /s)	Event type (T)	ECA (%)	R ₉₅ (mm)	ROS ₉₅ (mm)	Q ₀₁ (mm)	Q ₀₂ (mm)	Rainfall Q ₀₃ (mm)	error (mm)	Q1-2 (mm)	Q2-3 (mm)	Q1-3 (mm)	Affected? 0 or 1 ^b	Δ ECA (%)	Δ Q (%)	Affected? 0 or 1 ^b	Δ ECA (%)	Δ Q (%)	Affected? 0 or 1 ^b	Δ ECA (%)	Δ Q (%)
07-Nov-91	0.897	11.300	0	20.3	30.444	0.000	10.947	6.716	5.254	0.353	4.232	1.461	5.693	1	1.4	12.0	NA	NA	NA	1	4.9	52.0
11-Nov-91	0.967	13.200	0	20.3	37.915	0.000	13.463	8.193	6.373	-0.263	5.270	1.820	7.090	1	1.4	12.2	NA	NA	NA	1	4.9	52.7
15-Nov-91	0.880	21.700	0	20.3	62.188	0.000	21.277	12.632	9.647	0.423	8.644	2.985	11.629	1	1.4	12.7	NA	NA	NA	1	4.9	54.7
19-Nov-91	2.690	32.500	0	20.3	92.476	0.000	33.214	20.360	15.921	-0.714	12.854	4.439	17.293	1	1.4	12.0	NA	NA	NA	1	4.9	52.1
24-Nov-91	2.000	13.900	0	20.3	34.779	0.000	13.618	8.784	7.114	0.282	4.834	1.669	6.504	1	1.4	10.8	NA	NA	NA	1	4.9	47.8
03-Dec-91	2.520	12.500	0	20.3	35.826	0.000	14.552	9.572	7.853	-2.052	4.980	1.720	6.700	0	1.4	10.3	NA	NA	NA	1	4.9	46.0
05-Dec-91	4.750	18.400	0	20.3	45.588	0.000	20.277	13.940	11.752	-1.877	6.337	2.188	8.525	1	1.4	9.3	NA	NA	NA	1	4.9	42.0
08-Dec-91	5.410	21.100	0	20.3	44.189	0.000	20.573	14.431	12.310	0.527	6.142	2.121	8.263	1	1.4	8.8	NA	NA	NA	1	4.9	40.2
25-Dec-91	1.860	24.100	0	20.3	70.371	0.000	25.061	15.280	11.902	-0.961	9.782	3.378	13.159	1	1.4	12.1	NA	NA	NA	1	4.9	52.5
01-Jan-92	1.930	30.400	0	20.3	83.703	0.000	29.487	17.853	13.835	0.913	11.635	4.018	15.653	1	1.4	12.3	NA	NA	NA	1	4.9	53.1
09-Jan-92	0.619	28.000	0	20.3	85.389	0.000	28.542	16.673	12.575	-0.542	11.869	4.099	15.968	1	1.4	13.1	NA	NA	NA	1	4.9	55.9
15-Jan-92	1.710	16.600	1	29.2	28.579	-0.446	11.116	7.209	5.857	5.484	3.907	1.352	5.260	1	1.7	10.7	NA	NA	NA	1	7.0	47.3
23-Jan-92	2.750	20.600	1	29.2	33.850	7.301	16.623	10.852	8.906	3.977	5.771	1.946	7.717	1	1.7	10.5	NA	NA	NA	1	7.0	46.4
27-Jan-92	7.000	13.600	1	29.2	8.427	6.237	12.937	10.855	10.176	0.663	2.082	0.679	2.761	0	1.7	4.4	NA	NA	NA	1	7.0	21.3
29-Jan-92	7.040	33.600	0	20.3	74.615	0.000	32.350	21.979	18.397	1.250	10.371	3.582	13.953	1	1.4	9.5	NA	NA	NA	1	4.9	43.1
31-Jan-92	9.460	22.000	1	29.2	24.996	5.523	20.789	16.508	15.065	1.211	4.281	1.443	5.724	1	1.7	5.7	NA	NA	NA	1	7.0	27.5
02-Feb-92	6.930	30.200	0	20.3	64.927	0.000	29.066	20.042	16.925	1.134	9.025	3.117	12.141	1	1.4	9.2	NA	NA	NA	1	4.9	41.8
21-Feb-92	0.880	12.800	1	29.2	23.409	8.017	11.328	6.904	5.428	1.472	4.424	1.476	5.901	1	1.7	12.1	NA	NA	NA	1	7.0	52.1
24-Feb-92	2.540	8.450	1	29.2	14.771	8.974	10.726	7.363	6.259	-2.276	3.363	1.104	4.467	0	1.7	9.3	NA	NA	NA	0	7.0	41.6
16-Apr-92	1.500	10.400	0	20.3	27.140	0.000	10.557	6.785	5.482	-0.157	3.772	1.303	5.075	1	1.4	10.9	NA	NA	NA	1	4.9	48.1
26-Apr-92	1.000	10.100	1	29.2	22.492	11.394	12.301	7.511	5.930	-2.201	4.790	1.581	6.371	0	1.7	12.1	NA	NA	NA	1	7.0	51.8
29-Apr-92	2.740	8.340	1	29.2	23.143	-5.363	8.866	6.432	5.557	-0.526	2.434	0.875	3.309	0	1.7	8.0	NA	NA	NA	0	7.0	37.3
09-Jun-92	1.190	9.230	1	32.8	42.106	-2.653	14.192	8.726	6.822	-4.962	5.465	1.904	7.370	0	5.3	11.9	NA	NA	NA	0	10.6	51.9
31-Oct-92	1.865	14.700	1	32.8	33.922	9.139	16.255	10.206	8.176	-1.555	6.050	2.030	8.080	1	5.3	11.4	NA	NA	NA	1	10.6	49.7
01-Nov-92	11.000	18.900	1	32.8	6.301	10.175	18.127	15.766	15.016	0.773	2.362	0.750	3.112	1	5.3	3.5	NA	NA	NA	1	10.6	17.2
03-Nov-92	1.290	13.800	0	21.3	37.614	0.000	13.733	8.504	6.699	0.067	5.228	1.805	7.034	1	2.4	11.8	NA	NA	NA	1	5.9	51.2
06-Nov-92	1.550	20.200	0	21.3	64.450	0.000	22.778	13.819	10.726	-2.578	8.959	3.094	12.052	1	2.4	12.2	NA	NA	NA	1	5.9	52.9
26-Nov-92	0.892	8.780	0	21.3	24.799	0.000	9.101	5.654	4.464	-0.321	3.447	1.190	4.637	0	2.4	11.7	NA	NA	NA	1	5.9	51.0
29-Nov-92	1.220	8.110	0	21.3	32.193	0.000	11.886	7.411	5.866	0.699	4.475	1.545	6.020	1	2.4	11.6	0	2.4	26.3	NA	NA	NA
13-Dec-92	0.657	8.340	0	21.3	40.320	0.000	13.893	8.289	6.353	0.051	5.604	1.935	7.540	1	2.4	12.6	0	2.4	30.5	NA	NA	NA
26-Jan-93	2.750	11.049	0	21.3	53.259	0.000	20.497	13.094	10.538	-2.045	7.403	2.556	9.959	1	2.4	11.0	0	2.4	24.3	NA	NA	NA
03-Feb-93	2.470	5.960	1	32.8	3.196	23.503	11.755	7.879	6.691	-1.919	3.876	1.188	5.063	1	8.0	9.9	0	5.3	17.7	NA	NA	NA
02-Mar-93	0.618	13.100	1	32.8	44.509	49.850	31.964	18.499	14.169	-5.399	13.465	4.330	17.795	1	8.0	13.3	0	5.3	30.6	NA	NA	NA

^a All flow differences are reported as they were calculated, alongside a variable that is equal to zero if the DQP in question is unaffected as defined here, and 1 if the DQP is significantly affected. This number simply serves as a multiplier to reduce the insignificant flow changes to zero.

^b Classification variable to indicate whether the event has been affected by harvesting or not.

continued ...

APPENDIX C - continued.

Storm date	Observed quantities			Calculated quantities										Differences in peak flow				P1 vs. P2		P2 vs. P3		P1 vs. P3	
	Flow QBF ^a (m ³ /s)	Event type (T)	Event	ECA (%)	R _{sa} (mm)	ROS _{ad} (mm)	Rainfall		error (mm)	Q1-2 (mm)	Q2-3 (mm)	Q1-3 (mm)	Affected? 0 or 1 ^b	Δ ECA (%)	Δ Q (%)	Affected? 0 or 1 ^b	Δ ECA (%)	Δ Q (%)	Affected? 0 or 1 ^b	Δ ECA (%)	Δ Q (%)		
							Q _{P1} (mm)	Q _{P2} (mm)															
05-Mar-93	4.070	13.400	1	32.8	28.398	35.326	25.767	16.662	13.745	-3.262	9.105	2.917	12.022	1	8.0	10.7	0	5.3	21.2	NA	NA	NA	
21-Mar-93	2.280	21.600	1	32.8	71.507	53.299	43.819	26.098	20.320	-4.498	17.721	5.777	23.499	1	8.0	12.7	0	5.3	28.4	NA	NA	NA	
10-May-93	1.340	9.610	0	21.3	36.695	0.000	13.490	8.390	6.628	1.220	5.101	1.761	6.862	1	2.4	11.7	0	2.4	26.6	NA	NA	NA	
09-Jun-93	0.145	7.947	1	28.9	17.476	25.790	14.528	8.333	6.360	-0.386	6.195	1.974	8.168	1	1.4	13.5	0	4.1	31.0	NA	NA	NA	
13-Jun-93	1.370	5.680	0	19.8	24.338	0.000	9.496	6.113	4.945	-0.433	3.383	1.168	4.551	1	0.9	10.8	0	4.4	23.6	NA	NA	NA	
22-Aug-93	0.394	13.500	0	19.8	65.234	0.000	21.716	12.648	9.517	0.852	9.068	3.131	12.199	1	0.9	13.2	1	4.4	32.9	NA	NA	NA	
18-Nov-93	0.832	11.171	0	19.8	58.821	0.000	20.124	11.948	9.125	-0.777	8.176	2.823	10.999	1	0.9	12.7	0	4.4	30.9	NA	NA	NA	
Jan-94	2.810	6.760	0	19.8	17.312	0.000	8.847	6.441	5.610	0.319	2.406	0.831	3.237	0	0.9	7.9	0	4.4	14.8	NA	NA	NA	
Feb-94	1.160	23.200	1	28.9	67.224	50.731	40.283	23.532	18.073	-0.332	16.751	5.459	22.210	1	1.4	13.1	1	4.1	30.2	NA	NA	NA	
01-Mar-94	15.700	30.900	1	28.9	46.792	35.585	45.109	33.409	29.597	-2.509	11.699	3.812	15.511	1	1.4	7.5	0	4.1	12.9	NA	NA	NA	
01-Mar-94	15.700	30.900	1	28.9	26.702	26.795	35.606	27.982	25.522	2.918	7.624	2.461	10.084	1	1.4	6.0	1	4.1	9.6	NA	NA	NA	
12-Mar-94	2.180	7.330	0	19.8	20.925	0.000	9.307	6.398	5.394	0.932	2.909	1.004	3.913	0	0.9	9.3	0	4.4	18.6	NA	NA	NA	
01-Apr-94	3.570	5.840	0	19.8	14.228	0.000	8.708	6.731	6.048	-0.891	1.978	0.683	2.661	0	0.9	6.4	0	4.4	11.3	NA	NA	NA	
10-Apr-94	1.950	11.400	0	19.8	51.618	0.000	19.050	11.876	9.398	-0.476	7.175	2.478	9.653	1	0.9	11.6	0	4.4	26.4	NA	NA	NA	
18-Oct-94	1.080	5.060	0	18.0	24.666	0.000	9.272	5.844	4.660	-0.784	3.429	1.184	4.613	1	-0.9	11.3	0	2.6	25.4	NA	NA	NA	
24-Oct-94	1.390	22.500	1	25.4	69.612	45.081	39.425	23.167	17.842	-0.667	16.258	5.325	21.583	1	-2.1	13.0	1	3.2	29.8	NA	NA	NA	
25-Oct-94	10.900	17.200	0	18.0	23.665	0.000	20.141	16.851	15.715	0.349	3.289	1.136	4.425	0	-0.9	4.4	0	2.6	7.2	NA	NA	NA	
30-Oct-94	2.270	6.840	0	18.0	20.711	0.000	9.340	6.461	5.467	0.379	2.879	0.994	3.873	0	-0.9	9.1	0	2.6	18.2	NA	NA	NA	
21-Dec-94	2.690	23.600	0	18.0	118.089	0.000	41.564	25.149	19.481	-1.549	16.414	5.668	22.083	1	-0.9	12.3	1	2.6	29.1	NA	NA	NA	
07-Jan-95	2.770	9.650	0	18.0	28.680	0.000	12.508	8.521	7.144	1.129	3.987	1.377	5.363	0	-0.9	9.5	0	2.6	19.3	NA	NA	NA	
28-Jan-95	2.680	20.500	1	25.4	68.424	50.881	42.457	25.518	19.995	-5.018	16.940	5.523	22.463	1	-2.1	12.5	0	3.2	27.6	NA	NA	NA	
31-Jan-95	6.390	10.500	0	18.0	17.476	0.000	12.982	10.553	9.714	-0.053	2.429	0.839	3.268	0	-0.9	5.2	0	2.6	8.6	NA	NA	NA	
02-Feb-95	2.810	7.830	0	18.0	19.876	0.000	9.683	6.920	5.966	0.910	2.763	0.954	3.717	0	-0.9	8.3	0	2.6	16.0	NA	NA	NA	
20-Feb-95	2.410	9.490	0	18.0	25.550	0.000	11.077	7.525	6.299	1.965	3.551	1.226	4.778	0	-0.9	9.5	1	2.6	19.5	NA	NA	NA	
23-Feb-95	2.510	9.710	0	18.0	47.349	0.000	18.297	11.716	9.443	-2.006	6.581	2.273	8.854	1	-0.9	11.0	0	2.6	24.1	NA	NA	NA	
08-Mar-95	0.521	6.550	0	18.0	36.013	0.000	12.334	7.328	5.600	-0.778	5.006	1.729	6.734	1	-0.9	12.7	0	2.6	30.9	NA	NA	NA	
14-Mar-95	2.560	7.900	0	18.0	19.371	0.000	9.233	6.541	5.611	1.359	2.693	0.930	3.622	0	-0.9	8.5	0	2.6	16.6	NA	NA	NA	
01-May-95	2.150	5.370	0	18.0	17.817	0.000	8.259	5.783	4.928	-0.413	2.477	0.855	3.332	0	-0.9	8.8	0	2.6	17.4	NA	NA	NA	
07-Oct-95	1.560	6.020	0	17.5	23.782	0.000	9.931	6.226	5.084	-0.206	3.306	1.142	4.447	1	-1.4	10.5	0	2.1	22.5	NA	NA	NA	
09-Oct-95	2.080	9.360	0	17.5	38.445	0.000	14.904	9.560	7.715	-0.200	5.344	1.845	7.189	1	-1.4	10.9	0	2.1	23.9	NA	NA	NA	
13-Oct-95	1.900	25.600	0	17.5	108.145	0.000	37.421	22.389	17.198	3.211	15.032	5.191	20.223	1	-1.4	12.6	1	2.1	30.2	NA	NA	NA	
15-Oct-95	11.100	19.200	1	25.0	22.783	21.199	27.204	20.942	18.916	-1.742	6.262	2.026	8.288	1	-2.5	6.5	0	2.8	10.7	NA	NA	NA	
24-Oct-95	1.370	19.900	1	25.0	68.088	38.703	36.763	21.648	16.677	-1.748	15.115	4.971	20.086	1	-2.5	12.9	1	2.8	29.8	NA	NA	NA	

continued . . .

APPENDIX C - continued.

Storm date	Observed quantities			Calculated quantities					Differences in peak flow				P1 vs. P2		P2 vs. P3		P1 vs. P3					
	QBF (m³/s)	Flow (m³/s)	Event type (T)	ECA (%)	R _{sa} (mm)	ROS ₄ (mm)	Rainfall			error (mm)	Q1-2 (mm)	Q2-3 (mm)	Q1-3 (mm)	Affected? 0 or 1*	Δ ECA (%)	Δ Q (%)	Affected? 0 or 1*	Δ ECA (%)	Δ Q (%)			
							Q _{r1} (mm)	Q _{r2} (mm)	Q _{r3} (mm)													
07-Nov-95	0.436	43.000	1	25.0	109.538	82.475	63.918	36.651	27.764	6.349	27.267	8.887	36.154	1	-2.5	13.6	1	2.8	32.0	NA	NA	
13-Nov-95	5.350	17.700	1	25.0	21.236	37.582	25.650	17.211	14.538	0.489	8.439	2.673	11.112	1	-2.5	9.8	1	2.8	18.4	NA	NA	
15-Nov-95	10.900	20.900	1	25.0	13.897	25.430	25.501	19.856	18.070	1.044	5.644	1.786	7.430	1	-2.5	6.2	0	2.8	9.9	NA	NA	
16-Nov-95	7.580	42.400	1	25.0	103.209	76.771	68.082	42.528	34.196	-0.128	25.555	8.332	33.887	1	-2.5	11.6	1	2.8	24.4	NA	NA	
23-Nov-95	2.350	16.200	1	25.0	20.779	26.369	18.313	11.575	9.417	4.625	6.738	2.158	8.896	0	-2.5	11.3	1	2.8	22.9	NA	NA	
24-Nov-95	6.940	14.400	0	17.5	37.535	0.000	20.148	14.931	13.129	-0.531	5.217	1.802	7.019	1	-1.4	7.4	0	2.1	13.7	NA	NA	
27-Nov-95	6.020	22.700	1	25.0	28.618	42.203	30.373	20.233	17.002	2.467	10.140	3.231	13.370	1	-2.5	10.0	1	2.8	19.0	NA	NA	
09-Dec-95	0.692	30.000	0	17.5	125.795	0.000	41.798	24.313	18.274	5.687	17.486	6.038	23.524	1	-1.4	13.2	1	2.1	33.0	NA	NA	
17-Dec-95	8.330	13.450	0	17.5	10.412	0.000	12.891	11.443	10.944	2.007	1.447	0.500	1.947	0	-1.4	3.0	0	2.1	4.6	NA	NA	
01-Jan-96	5.600	14.000	1	25.0	9.490	24.667	17.766	12.845	11.304	1.155	4.920	1.541	6.461	1	-2.5	8.0	0	2.8	13.6	NA	NA	
06-Jan-96	5.600	13.100	0	17.5	44.632	0.000	20.934	14.730	12.588	-1.630	6.204	2.142	8.346	1	-1.4	8.7	0	2.1	17.0	NA	NA	
08-Jan-96	6.610	14.550	1	25.0	12.091	24.987	19.873	14.544	12.864	0.006	5.329	1.680	7.009	1	-2.5	7.7	0	2.8	13.1	NA	NA	
10-Jan-96	7.540	39.203	1	25.0	97.749	47.835	56.535	35.964	29.167	3.239	20.571	6.797	27.368	1	-2.5	11.1	1	2.8	23.3	NA	NA	
04-Apr-96	0.873	24.284	0	17.5	134.010	0.000	44.683	26.055	19.623	-1.771	18.627	6.432	25.060	1	-1.4	13.2	1	2.1	32.8	NA	NA	
07-Apr-96	3.519	9.482	0	17.5	24.519	0.000	12.005	8.597	7.420	0.885	3.408	1.177	4.585	0	-1.4	8.3	0	2.1	15.9	NA	NA	
08-Apr-96	4.041	5.341	0	17.5	21.676	0.000	11.674	8.661	7.620	-3.320	3.013	1.040	4.053	1	-1.4	7.4	0	2.1	13.7	NA	NA	
23-Apr-96	1.510	6.120	0	17.5	21.878	0.000	8.854	5.813	4.763	0.307	3.041	1.050	4.091	0	-1.4	10.4	0	2.1	22.1	NA	NA	
20-Oct-96	1.240	11.800	1	25.4	20.484	35.735	20.098	12.034	9.478	-0.234	8.065	2.556	10.620	1	-2.1	12.5	0	3.2	27.0	NA	NA	
26-Oct-96	1.580	13.700	1	25.4	16.774	22.053	14.680	9.128	7.353	4.572	5.551	1.776	7.327	0	-2.1	11.7	1	3.2	24.1	NA	NA	
11-Nov-96	2.890	5.130	0	18.5	10.080	0.000	6.581	5.180	4.696	-0.050	1.401	0.484	1.885	0	-0.4	6.0	0	3.1	10.3	NA	NA	
31-Dec-96	0.111	7.914	0	18.5	45.224	0.000	14.869	8.583	6.413	-0.669	6.286	2.171	8.457	1	-0.4	13.4	0	3.1	33.9	NA	NA	
28-Jan-97	0.293	9.840	0	18.5	48.365	0.000	16.101	9.378	7.057	0.461	6.723	2.322	9.044	1	-0.4	13.2	0	3.1	32.9	NA	NA	
11-Feb-97	0.280	5.324	0	18.5	8.924	0.000	3.228	1.988	1.560	3.336	1.240	0.428	1.669	0	-0.4	11.9	1	3.1	27.5	NA	NA	
16-Feb-97	3.966	5.904	0	18.5	17.676	0.000	10.284	7.827	6.978	-1.922	2.457	0.848	3.305	1	-0.4	6.8	0	3.1	12.2	NA	NA	
17-Mar-97	0.277	7.489	0	18.5	60.112	0.000	19.912	11.557	8.671	-4.067	8.356	2.885	11.241	1	-0.4	13.3	0	3.1	33.3	NA	NA	
18-Mar-97	5.983	7.380	0	18.5	27.930	0.000	15.926	12.043	10.703	-4.664	3.882	1.341	5.223	1	-0.4	6.9	0	3.1	12.5	NA	NA	
14-Apr-97	0.896	7.581	1	25.4	22.318	11.762	12.249	7.430	5.841	0.151	4.820	1.589	6.408	1	-2.1	12.2	0	3.2	27.2	NA	NA	
24-Apr-97	1.690	7.905	1	25.4	14.315	21.123	13.691	8.617	7.000	-0.712	5.074	1.617	6.690	1	-2.1	11.4	0	3.2	23.1	NA	NA	
28-May-97	3.374	6.870	0	18.5	14.934	0.000	8.715	6.639	5.922	0.232	2.076	0.717	2.793	0	-0.4	6.8	0	3.1	12.1	NA	NA	
30-May-97	3.101	5.081	0	18.5	8.681	0.000	6.365	5.159	4.742	-0.078	1.207	0.417	1.623	0	-0.4	5.2	0	3.1	8.8	NA	NA	
16-Jun-97	2.167	6.816	0	18.2	23.873	0.000	10.253	6.935	5.789	1.028	3.318	1.146	4.464	NA	NA	NA	0	-0.7	16.5	1	2.8	43.5
18-Jun-97	4.165	4.953	0	18.2	10.514	0.000	8.176	6.714	6.210	-1.257	1.461	0.505	1.966	NA	NA	NA	0	0	2.8	0	2.8	
27-Jun-97	3.082	7.183	0	18.2	22.420	0.000	10.823	7.706	6.630	0.553	3.116	1.076	4.193	NA	NA	NA	0	-0.7	14.0	1	2.8	38.7

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APPENDIX C - continued.

Storm date	Observed quantities			Calculated quantities										Differences in peak flow				P1 vs. P2		P2 vs. P3		P1 vs. P3		
	QBF (m³/s)	QP (m³/s)	Event type (I)	ECA (%)	R ₅₀ (mm)	ROS ₅₀ (mm)	Q ₁₀ (mm)	Q ₂₀ (mm)	Q ₃₀ (mm)	error (mm)	Q1-2 (mm)	Q2-3 (mm)	Q1-3 (mm)	Affected? 0 or 1 ^a	Δ ECA (%)	Δ Q (%)	Affected? 0 or 1 ^a	Δ ECA (%)	Δ Q (%)	Affected? 0 or 1 ^a	Δ ECA (%)	Δ Q (%)		
07-Jul-97	1.273	6.656	0	18.2	31.923	0.000	11.858	7.421	5.889	0.767	4.437	1.532	5.970	NA	NA	NA	NA	NA	0	-0.7	20.6	1	2.8	50.3
26-Aug-97	2.021	7.404	0	18.2	21.702	0.000	9.379	6.362	5.320	2.084	3.017	1.042	4.058	NA	NA	NA	NA	NA	0	-0.7	16.4	0	2.8	43.3
16-Sep-97	1.062	7.279	0	18.2	41.976	0.000	14.895	9.060	7.046	0.234	5.835	2.015	7.850	NA	NA	NA	NA	NA	0	-0.7	22.2	1	2.8	52.7
25-Sep-97	0.291	7.757	0	18.2	44.411	0.000	14.809	8.636	6.505	1.253	6.173	2.132	8.305	NA	NA	NA	NA	NA	0	-0.7	24.7	1	2.8	56.1
27-Sep-97	3.102	5.652	0	18.2	14.632	0.000	8.306	6.272	5.570	0.083	2.034	0.702	2.736	NA	NA	NA	NA	NA	0	-0.7	11.2	0	2.8	32.9
29-Sep-97	2.028	16.203	1	25.6	40.251	37.887	28.163	17.037	13.438	2.766	11.126	3.599	14.725	NA	NA	NA	NA	NA	0	-1.9	21.1	1	3.4	52.3
01-Oct-97	3.349	13.170	0	18.2	95.361	0.000	34.906	21.651	17.073	-3.904	13.255	4.577	17.833	NA	NA	NA	NA	NA	1	-0.7	21.1	1	2.8	51.1
03-Oct-97	3.867	7.829	0	18.2	36.147	0.000	16.192	11.168	9.432	-1.603	5.024	1.735	6.759	NA	NA	NA	NA	NA	1	-0.7	15.5	1	2.8	41.7
09-Oct-97	3.148	4.942	0	18.2	21.547	0.000	10.613	7.618	6.584	-1.642	2.995	1.034	4.029	NA	NA	NA	NA	NA	0	-0.7	13.6	1	2.8	38.0
15-Oct-97	2.369	10.910	0	18.2	58.507	0.000	21.774	13.641	10.833	0.077	8.132	2.808	10.941	NA	NA	NA	NA	NA	1	-0.7	20.6	1	2.8	50.2
24-Oct-97	1.500	6.826	0	18.2	18.920	0.000	7.878	5.248	4.340	2.486	2.630	0.908	3.538	NA	NA	NA	NA	NA	0	-0.7	17.3	0	2.8	44.9
28-Oct-97	2.104	7.233	0	18.2	44.084	0.000	16.770	10.642	8.526	-1.293	6.128	2.116	6.951	NA	NA	NA	NA	NA	1	-0.7	19.9	1	2.8	41.4
29-Oct-97	5.501	12.613	0	18.2	69.842	0.000	29.040	19.332	15.980	-3.367	9.708	3.352	9.694	NA	NA	NA	NA	NA	1	-0.7	17.3	1	2.8	33.4
02-Nov-97	3.673	13.082	1	25.6	37.433	34.108	27.850	17.667	14.370	-1.288	10.183	3.298	12.193	NA	NA	NA	NA	NA	1	-1.9	18.7	1	3.4	43.8
05-Nov-97	3.349	14.655	1	25.6	33.350	35.218	26.524	16.746	13.596	1.059	9.778	3.150	13.987	NA	NA	NA	NA	NA	0	-1.9	18.8	1	3.4	52.7
22-Nov-97	0.372	8.097	1	25.6	31.890	33.563	22.097	12.764	9.757	-1.660	9.333	3.007	10.680	NA	NA	NA	NA	NA	1	-1.9	23.6	1	3.4	48.3
12-Dec-97	2.049	11.166	0	18.2	75.699	0.000	27.014	16.492	12.858	-1.693	10.522	3.634	12.463	NA	NA	NA	NA	NA	1	-0.7	22.0	1	2.8	46.1
27-Dec-97	2.927	13.584	1	25.6	46.212	36.076	30.523	18.832	15.027	-1.443	11.690	3.805	14.053	NA	NA	NA	NA	NA	1	-1.9	20.2	1	3.4	46.0
17-Jan-98	1.627	7.437	0	18.2	37.081	0.000	13.943	8.789	7.009	0.428	5.154	1.780	7.362	NA	NA	NA	NA	NA	0	-0.7	20.3	1	2.8	52.8
11-Feb-98	1.150	9.451	1	25.6	30.062	35.250	22.955	13.630	10.636	-1.185	9.325	2.994	11.135	NA	NA	NA	NA	NA	1	-1.9	22.0	1	3.4	48.5
18-Feb-98	1.908	13.537	1	25.6	51.593	38.651	31.981	19.166	14.989	-1.452	12.814	4.177	15.539	NA	NA	NA	NA	NA	1	-1.9	21.8	1	3.4	48.6
11-Mar-98	2.719	8.703	1	25.6	15.914	35.464	20.204	12.814	10.490	-1.787	7.390	2.324	7.927	NA	NA	NA	NA	NA	1	-1.9	18.1	1	3.4	39.2
12-Oct-98	1.145	14.775	0	17.0	55.235	0.000	19.312	11.634	8.983	5.792	7.678	2.651	4.537	NA	NA	NA	NA	NA	0	-1.9	22.8	1	-3.8	23.5
16-Oct-98	1.842	14.631	0	17.0	56.342	0.000	20.467	12.636	9.931	4.700	7.832	2.704	5.836	NA	NA	NA	NA	NA	0	-1.9	21.4	1	-3.8	28.5
11-Nov-98	1.036	15.964	1	24.2	48.326	37.465	29.523	17.336	13.368	2.596	12.187	3.968	13.559	NA	NA	NA	NA	NA	0	-3.3	22.9	1	-6.8	45.9
14-Nov-98	3.184	7.109	0	17.0	17.025	0.000	9.180	6.813	5.996	1.113	2.366	0.817	2.070	NA	NA	NA	NA	NA	0	-1.9	12.0	0	-3.8	22.6
15-Nov-98	6.479	8.768	0	17.0	15.896	0.000	12.568	10.359	9.596	-0.828	2.210	0.763	3.800	NA	NA	NA	NA	NA	0	-1.9	7.4	1	-3.8	30.2
19-Nov-98	2.326	11.155	0	17.0	49.444	0.000	18.770	11.898	9.524	1.631	6.873	2.373	7.615	NA	NA	NA	NA	NA	0	-1.9	19.9	1	-3.8	40.6
09-Dec-98	1.142	14.027	1	24.2	41.884	36.206	27.121	16.013	12.410	1.617	11.108	3.604	13.094	NA	NA	NA	NA	NA	0	-3.3	22.5	1	-6.8	48.3
12-Dec-98	3.463	18.693	1	24.2	58.015	36.703	35.193	21.770	17.371	1.322	13.423	4.400	16.500	NA	NA	NA	NA	NA	1	-3.3	20.2	1	-6.8	46.9
15-Dec-98	3.887	11.166	1	24.2	5.250	34.473	17.726	11.963	10.194	0.972	5.763	1.769	6.560	NA	NA	NA	NA	NA	0	-3.3	14.8	1	-6.8	37.0
27-Dec-98	0.861	5.992	0	17.0	27.670	0.000	10.002	6.156	4.828	1.164	3.846	1.328	4.010	NA	NA	NA	NA	NA	0	-1.9	21.6	1	-3.8	40.1
30-Dec-98	3.370	10.770	1	24.2	15.002	34.676	20.384	13.236	10.990	-0.220	7.148	2.246	9.614	NA	NA	NA	NA	NA	0	-3.3	17.0	1	-6.8	47.2

continued ...

APPENDIX C - continued.

Storm date	Observed quantities			Calculated quantities							Differences in peak flow				P1 vs. P2		P2 vs. P3		P1 vs. P3			
	QBF (m³/s)	Flow (m³/s)	Event type (T)	ECA (%)	R _{max} (mm)	ROS _{adj} (mm)	Q _{r1} (mm)	Q _{r2} (mm)	Q _{r3} (mm)	error (mm)	Q1-2 (mm)	Q2-3 (mm)	Q1-3 (mm)	Affected? 0 or 1*	Δ ECA (%)	Δ Q (%)	Affected? 0 or 1*	Δ ECA (%)	Δ Q (%)			
09-Jan-99	3.308	6.030	0	17.0	5.158	0.000	5.453	4.736	4.489	1.541	0.717	0.248	-0.577	NA	NA	NA	0	-1.9	5.2	0	-3.8	-10.6
10-Jan-99	3.282	15.800	1	24.2	42.366	36.005	29.650	18.505	14.887	0.913	11.145	3.618	13.850	NA	NA	NA	1	-3.3	19.6	1	-6.8	46.7
13-Jan-99	3.580	15.700	1	24.2	46.689	35.569	31.253	19.570	15.764	-0.064	11.683	3.806	15.553	NA	NA	NA	1	-3.3	19.4	1	-6.8	49.8
19-Apr-99	4.554	7.780	0	17.0	11.356	0.000	8.894	7.316	6.771	1.009	1.578	0.545	1.114	NA	NA	NA	0	-1.9	8.1	0	-3.8	12.5
24-Apr-99	5.800	12.745	1	24.2	5.492	33.824	19.768	14.066	12.314	0.431	5.702	1.752	7.023	NA	NA	NA	0	-3.3	14.2	1	-6.8	35.5
05-May-99	2.161	8.827	1	24.2	19.642	36.114	21.001	12.998	10.466	-1.639	8.003	2.532	12.174	NA	NA	NA	1	-3.3	24.2	1	-6.8	58.0
30-May-99	4.369	11.350	1	24.2	7.009	33.189	18.417	12.597	10.800	0.550	5.820	1.797	7.067	NA	NA	NA	0	-3.3	16.6	1	-6.8	38.4
04-Jun-99	7.088	10.088	0	17.0	15.293	0.000	13.066	10.940	10.206	-0.118	2.126	0.734	2.978	NA	NA	NA	0	-1.9	7.2	0	-3.8	22.8
06-Jul-99	4.659	10.370	0	17.0	50.508	0.000	21.777	14.756	12.332	-1.962	7.021	2.424	11.407	NA	NA	NA	1	-1.9	19.7	1	-3.8	52.4
27-Oct-99	0.771	10.414	0	15.5	59.203	0.000	20.179	11.950	9.108	1.306	8.229	2.842	9.765	NA	NA	NA	0	-3.4	31.2	1	-5.3	48.4
29-Oct-99	3.220	9.932	0	15.5	54.017	0.000	21.280	13.772	11.179	-1.247	7.508	2.593	11.348	NA	NA	NA	1	-3.4	23.2	1	-5.3	53.3
06-Nov-99	0.923	8.815	1	22.1	12.052	33.519	16.244	9.675	7.621	1.194	6.569	2.053	7.429	NA	NA	NA	0	-5.4	26.9	1	-8.9	45.7
08-Nov-99	2.704	19.901	1	22.1	75.908	43.962	42.600	25.630	20.052	-0.151	16.970	5.578	22.699	NA	NA	NA	1	-5.4	27.8	1	-8.9	53.3
15-Nov-99	4.221	12.562	1	22.1	28.025	33.398	25.169	16.398	13.583	-1.021	8.772	2.815	12.608	NA	NA	NA	1	-5.4	20.7	1	-8.9	50.1
19-Nov-99	1.451	5.837	0	15.5	41.716	0.000	15.254	9.456	7.453	-1.616	5.799	2.002	9.417	NA	NA	NA	1	-3.4	26.9	1	-5.3	61.7
24-Nov-99	1.256	6.002	0	15.5	16.381	0.000	6.772	4.495	3.709	2.293	2.277	0.786	0.770	NA	NA	NA	0	-3.4	21.2	0	-5.3	11.4
27-Nov-99	1.013	6.304	1	22.1	8.912	35.961	16.143	9.654	7.644	-1.340	6.489	2.010	9.839	NA	NA	NA	1	-5.4	26.3	1	-8.9	61.0
29-Nov-99	2.656	8.151	0	15.5	58.657	0.000	22.150	13.997	11.181	-3.030	8.153	2.816	13.999	NA	NA	NA	1	-3.4	25.2	1	-5.3	63.2
20-May-00	2.183	9.207	0	15.5	36.628	0.000	14.429	9.338	7.579	1.627	5.091	1.758	5.222	NA	NA	NA	0	-3.4	23.2	1	-5.3	36.2
26-Jul-00	0.764	7.392	0	15.5	40.509	0.000	14.076	8.446	6.501	0.891	5.631	1.944	6.684	NA	NA	NA	0	-3.4	29.9	1	-5.3	47.5
19-Oct-00	1.528	15.906	1	20.3	51.130	36.696	30.740	18.275	14.206	1.700	12.465	4.069	14.834	NA	NA	NA	0	3.1	28.6	1	-10.7	48.3
03-Nov-00	1.030	10.854	1	20.3	30.685	38.391	24.077	14.207	11.045	-0.191	9.870	3.162	13.223	NA	NA	NA	1	3.1	28.6	1	-10.7	54.9
24-Nov-00	0.879	13.721	0	13.9	73.593	0.000	24.993	14.764	11.231	2.490	10.229	3.532	11.272	NA	NA	NA	0	-3.3	31.5	1	-6.9	45.1
25-Dec-00	1.644	9.572	1	20.3	25.944	35.895	22.393	13.546	10.721	-1.149	8.847	2.825	11.671	NA	NA	NA	1	3.1	26.3	1	-10.7	52.1
01-Jan-01	1.225	11.297	1	20.3	27.769	36.838	22.826	13.588	10.635	0.662	9.238	2.954	12.192	NA	NA	NA	0	3.1	27.8	1	-10.7	53.4
03-Jan-01	4.069	8.376	0	13.9	37.768	0.000	16.951	11.701	9.888	-1.513	5.250	0.300	5.550	NA	NA	NA	1	-3.3	3.0	1	-6.9	32.7
11-Oct-01	0.902	6.263	0	12.3	26.273	0.000	9.593	5.942	4.680	1.583	3.652	2.844	6.496	NA	NA	NA	0	-3.1	60.8	0	-8.5	67.7
22-Oct-01	1.407	7.399	0	12.3	47.454	0.000	17.074	10.478	8.200	-0.801	6.596	1.477	8.073	NA	NA	NA	1	-3.1	18.0	1	-8.5	47.3
25-Oct-01	0.919	12.787	1	18.9	47.004	36.423	28.609	16.758	12.899	-0.112	11.851	3.747	15.598	NA	NA	NA	1	-3.3	29.0	1	-12.1	54.5
03-Nov-01	0.988	11.611	1	18.9	38.118	37.214	26.056	15.325	11.858	-0.246	10.732	3.221	13.952	NA	NA	NA	1	-3.3	27.2	1	-12.1	53.5
08-Nov-01	2.078	11.636	0	12.3	50.934	0.000	18.973	11.893	9.448	2.188	7.080	4.633	11.712	NA	NA	NA	0	-3.1	49.0	1	-8.5	61.7
11-Nov-01	1.378	11.187	1	18.9	42.916	35.995	27.656	16.435	12.792	-1.605	11.221	2.039	13.260	NA	NA	NA	1	-3.3	15.9	1	-12.1	47.9
14-Nov-01	4.086	20.187	1	18.9	73.668	39.039	41.791	25.852	20.598	-0.411	15.940	4.843	20.783	NA	NA	NA	1	-3.3	23.5	1	-12.1	49.7

APPENDIX D: VALIDATION OF RAIN-ON-SNOW ADJUSTMENT FACTOR

The rain-on-snow adjustment factor (ROS_{adj}) is an empirically derived factor that works together with another derived factor, the basic rainfall (R_{sb}) to improve the predictability of peak flows. Because it is not a physically based parameter, an alternate method of estimating a similar parameter using a more physically based approach was needed to validate this part of the model.

The processes that contribute energy to rain-on-snow melt are well known. The basic energy balance method is based on the energy available for melt at a point as given by Male and Gray (1981):

$$Q_M = Q_S + Q_L + Q_H + Q_E + Q_G + Q_R - dU/dt$$

where,

Q_S = shortwave radiation,

Q_L = longwave radiation,

Q_H = sensible heat flux,

Q_E = latent heat flux,

Q_G = ground heat flux,

Q_R = heat from rain, and

dU = rate of change of energy stored in the snowpack.

During rain-on-snow melt, the most important terms are the latent and sensible heat fluxes as demonstrated by Berris and Harr (1987). Measured melt and calculated energy budget terms were in agreement for clear-cut and forested plots and showed

that total melt in the clearcut was about twice that in the forested plot (Table D-1). In particular, the eddy fluxes were boosted 2.8X by the clearcut relative to the forest.

The problem in estimating these parameters at the watershed scale is that they are governed by wind speed, a highly site-specific parameter. Church (1988) has provided a graphical approximation of the additional yield from the snowpack during rain-on-snow melt as a function of wind speed, mean air temperature and daily rainfall (Figure D-1). Using meteorological data from the upper Stephanie snow gauge, and assuming a potential enhancement of 2.8X as suggested by Berris and Harr, the volume of water that could be yielded by the snowpack during selected rain-on-snow events was estimated using Figure D-1 to compare to the rain-on-snow adjustment factor (Table D-2, Figure D-2).

There is reasonable agreement between the two methods. The following should be noted: The method given by Church is based on daily rainfall (i.e., rain that falls during a discrete 24-h period), but is applied to the parameter R_{sb} , which is a derived parameter to represent basin-average precipitation of storms as opposed to discrete time periods. The wind and temperature data are from Stephanie Creek. Since the site is at the upper limit of the rain-on-snow zone, temperatures will be higher for the part of the watershed actively involved in rain-on-snow melt. Therefore, the band of rain-on-snow melt on Figure D-2 is probably higher than what is estimated by the Church and Berris and Harr method. The dashed line represents a more realistic upper limit to the rain-on-snow factor based on temperature lapse rates during rain-on-snow conditions.

These calculations serve to validate the rain-on-snow adjustment factor.

Table D-1. Energy balance measurements during rain-on-snow 11-12 February 1984 (Berris and Harr 1987).

Energy source	Clearcut plot			Forested plot			Ratios	
	Predicted melt		Measured melt (mm)	Predicted melt		Measured melt (mm)	Calculated (cc/forest)	Measured (cc/forest)
	(mm)	(%)		(mm)	(%)			
Q_S	0.3	1		0.0	0			
Q_L	2.9	13		2.8	25			
Q_H	7.8	35		2.7	24		2.89	
Q_E	4.8	22		1.8	16		2.67	
Q_R	6.4	29		3.9	35		1.64	
Eddy Flux ($Q_H + Q_E$)	12.6	57		4.5	40		2.80	
Total	22.2	100	25.1	11.2	100	11.9	1.98	2.11

Table D-2. Comparison of rain-on-snow adjustment factor with rain-on-snow melt as estimated by Church's method with adjustment for clearcut conditions.

Event date	R_{sn}	ROS_{adj}	Stephanie Creek data		ROS melt (Church)		Berris and Harr
			Mean daily temperature (deg C)	Mean daily wind speed (km/h)	Daily melt as proportion of rain (mm)	Daily melt as derived melt (mm)	Derived melt augmented by potential change due to clearcut
15-Oct-95	22.783	21.199	7.8	3.4	0.57	13.0	29.9
24-Oct-95	68.088	38.703	4.3	3.1	0.22	15.3	35.1
7-Nov-95	109.538	82.475	2.0	6.2	0.15	16.4	37.8
13-Nov-95	21.236	37.582	3.5	3.0	0.61	13.0	29.9
15-Nov-95	13.897	25.430	7.0	4.5	0.70	9.7	22.4
16-Nov-95	103.209	76.771	5.5	6.4	0.25	25.8	59.3
23-Nov-95	20.779	26.369	7.2	3.6	0.55	11.4	26.3
26-Oct-96	16.774	22.053	2.5	2.9	0.26	4.3	9.9
14-Apr-97	22.318	11.762	2.8	4.0	0.30	6.7	15.4
24-Apr-97	14.315	21.123	5.2	3.1	0.45	6.4	14.8
2-Nov-97	37.433	34.108	6.8	4.2	0.50	18.7	43.0
5-Nov-97	33.350	35.218	7.0	2.2	0.47	15.7	36.1
22-Nov-97	31.890	33.563	3.1	23.3	0.60	19.1	44.0
18-Feb-98	51.593	38.651	2.7	10.2	0.25	12.9	29.7

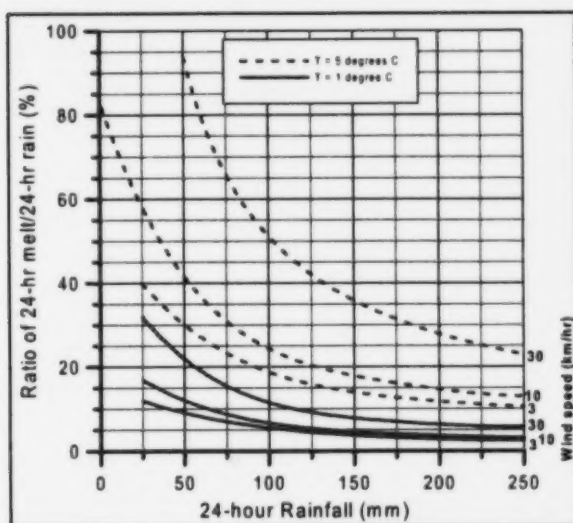


Figure D-1. A graphical method of estimating rain-on-snow melt as a function of daily rainfall, mean daily temperature, and mean daily wind speed.

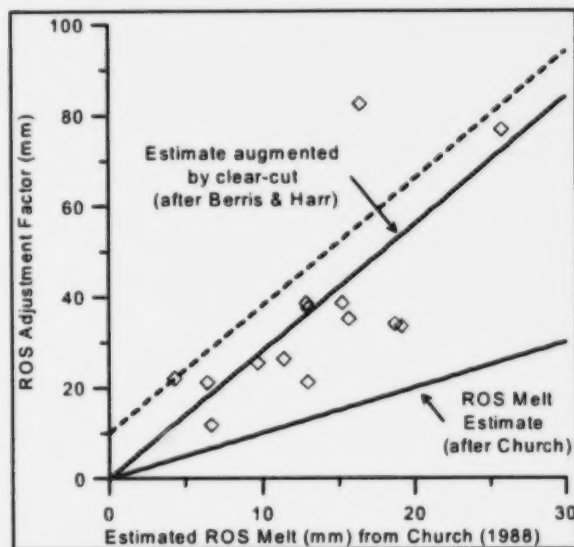


Figure D-2. Rain-on-snow adjustment factor compared to estimated snowpack yield after Church (1988) and with enhancement due to the clearcut after Berris and Harr (1986).

NOTES

NOTES

TR-022 Disclaimer

The results presented in this paper represent a first step towards the interpretation of ECA in its effect on peak streamflow. Very substantial changes in peak flow were documented for relatively small changes in ECA at Russell Creek. While the research has been judged sound under critical review, the method (meteorological control) used to assess these changes is not the standard method and has yet to be accepted by the scientific community at large. Furthermore, the method has been applied to one watershed under a limited range of ECA conditions. Therefore the results of this analysis are not ready for general application. The following steps must be taken:

- The meteorological control method must be evaluated alongside the standard paired watershed method to validate its utility at assessing changes in peak flow. This must be done in an experimental watershed that has both a control watershed and the appropriate meteorological data.
- The product of the above analysis will be submitted to a refereed journal (Water Resources Research) for publication.
- Once accepted the meteorological control method can be applied to other logged watersheds with a range of morphological characteristics.
- Once the above steps have been taken, then a general model of the relationship between ECA and peak streamflow will begin to emerge.

